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^{14}C - Chronology

Editors:

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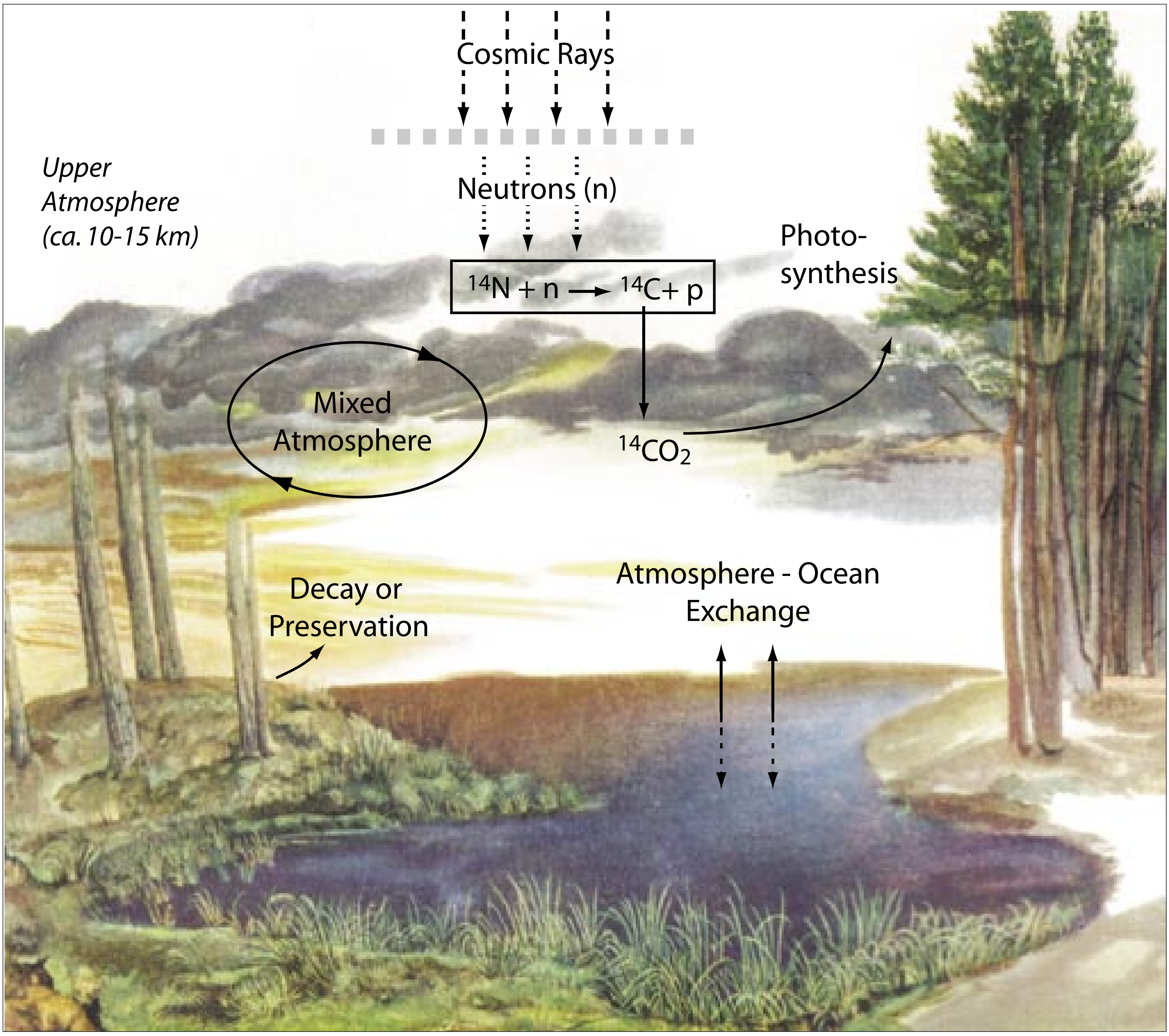

Production and cycling of radiocarbon: *Thermal neutrons originate from primary cosmic rays and react with (^{14}N) to produce ^{14}C in the upper troposphere and the stratosphere. The ^{14}C atoms are then oxidized to radioactive CO_2, which is mixed uniformly in the atmosphere and enters the global carbon cycle. The ^{14}C content of living organisms remains in equilibrium with the content of the reservoir in which they feed (take up ^{14}C). Death ends the balance between the uptake and decay of ^{14}C. The ^{14}C content diminishes at a steady rate with a half-life of 5730 years. Measuring the ^{14}C content in carbon-bearing material (wood, carbonate, organic matter) thus allows its age to be determined. If preserved and analyzed today, the trees that Albrecht Dürer depicted in 1496/97 in this painting, "Sonnenuntergang - Weiher im Walde", would contain approx. 95% of modern ^{14}C content.*

^{14}C-Chronology

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The radiocarbon dating method is commonly used to estimate the age of carbon-bearing material deposited in nature during the last 50 kyr. During nearly six decades of its application, the method has become a research discipline in itself. An ever-growing demand for reliable chronologies drives developments in preparative and measurement techniques. The need for calibration of the ^{14}C timescale, which has been the main challenge posed by the ^{14}C dating method almost from the beginning, has resulted in extended studies of suitable archives (trees, lake sediments, corals, stalagmites), as well as the development of calibration programs. All these developments were possible because of interdisciplinary collaborations. The exciting questions emerging as the work continues call for closer collaboration to keep the communities informed and interacting. For example, recent discussions on the timing of the Neanderthal extinction, the dispersion of modern Homo sapiens across Europe, and the possible connections to the climate changes that took place around that time of meltwater event Heinrich 4, rely heavily on the radiocarbon timescale and calibration. Our knowledge of paleo-reservoir ages, which is critical for marine records, is still very limited and a combined effort of the paleo and ^{14}C communities is needed. Furthermore, new calibration tools are now available and the benefits of using them should be presented to the paleocommunity.

In this issue of *PAGES news*, nine contributions present overview and progress reports on new developments in ^{14}C dating method and applications: The complex global cycle of the cosmogenic isotope ^{14}C is addressed by Konrad Hughen. He presents an overview of the recent reconstructions of Δ^{14}C (the measure of variability in the atmospheric ^{14}C content), which also contribute to the effort to extend the radiocarbon calibration curve back to the limit of the method (ca. 50-60 kyr BP). The progress and future prospects of the extension of the calibration curve is the focus of the IntCal group, presented in this issue by Paula Reimer. Promising new results from dating ancient Kauri wood from New Zealand (OIS3) were obtained by Alan Hogg and co-workers. Work towards more precise chronologies depends on the quality of radiocarbon ages. Results of two recent inter-comparison exercises (FIRI and VIRI) are reported by Marian Scott. In the contribution from Ron and Paula Reimer, spatial variability of marine reservoir ages is addressed; an important correction included in the calibration program and needed for marine records. Reconstruction of paleoreservoir ages is addressed by Pieter Grootes and Michael Sarnthein. Christopher Bronk Ramsey describes the Bayesian approach to calibrating sequences of ^{14}C ages using OxCal. A similar approach using the Bpeat code based on the MexCal program is presented by Maarten Blaauw. The higher precision of chronologies based on such approaches is illustrated by examples discussed in the contribution by David Lowe, Rewi Newnham and myself.

These are only a few examples of ^{14}C research activities that aim to improve the radiocarbon timescale and our understanding of complex processes that complicate this otherwise very straightforward method. We are all looking forward to the new, exciting data and even closer collaboration between the paleo and ^{14}C communities.

PAGES calendar 2007

April 11 - 14, 2007, Nanjing, China
2nd LIMPACS Salinity, Climate Change and Salinisation Workshop

Further Information:
www.geog.ucl.ac.uk/ecrc/limpacs/events.htm

May 19 - 24, 2007, Obergurgel, Austria
Ocean Controls in Abrupt Climate Change
ESF-FWF Conference in Partnership with LFUI

Further Information:
www.pages.unibe.ch/calendar/2007/ESF_Conference_announcement.pdf

July 11 - 14, 2007, Barcelona, Spain
4th International Limnogeology Congress

Further Information:
www.ilic2007.com/

July 28 - August 3, Cairns, Australia
XVII INQUA Congress 2007

Further Information:
www.inqua2007.net.au

August 27 - 31, 2007, Beijing, China
Third Alexander von Humboldt International Conference: East Asian Summer Monsoon, past, present and future

Further Information:
www.pages.unibe.ch/calendar/2007/monsoon_simp.pdf

August 27 - 31, 2007, Hamburg, Germany
Second International Conference on Earth System Modeling

Further Information:
www.mpimet.mpg.de/icesm

Inside Pages

There will be some new faces at the PAGES IPO and on the PAGES SSC at the start of 2007.

Leaving Science Officer

After 6 years at the IPO, **Christoph Kull** is moving on to work for the Swiss "Advisory Body on Climate Change" (OcCC), whose role is to formulate recommendations on questions regarding climate and global change for politicians and the federal administration. While he will certainly be missed, his presence will still be felt for a long time, given his work on many ongoing activities, as well as 15 co-edited PAGES newsletters, countless PPT teaching slides and photographs, and other products that you will still be able to download from our online Product Database. We thank him for his services to the paleoscience community, wish him the best of luck and success in his new post, and hope to meet him frequently in the future as an active member of the PAGES community. His successor will be presented in the next *PAGES News*.

Outgoing PAGES SSC members

At the end of 2006, PAGES Scientific Steering Committee (SSC) says farewell to **Carol Crumley** (USA), **José Ignacio Martínez** (Colombia), and **Ryuji Tada** (Japan). We thank them for their contributions to PAGES, and their help and dedication during their time on the Committee. We are sure that they will continue to remain engaged in PAGES activities.

Incoming PAGES SSC members

PAGES welcomes three new members to its SSC in 2007. **Takeshi Nakatsuka** (Japan) is Assistant Professor in Geochemistry at Hokkaido University. He has a scientific background in both modern ocean biogeochemistry as well as paleo applications in marine biogeochemistry, and is now extending towards paleoenvironmental studies on land. **José D. Carriquiry** (Mexico) is a professor at the Oceanographic Research Institute (Marine Geochemistry Group) of the Universidad Autónoma de Baja California at Ensenada. His scientific expertise in coral paleoclimatology led him to active involvement in the PAGES/CLIVAR initiative on Annual Records of Tropical Systems (ARTS). This expertise will be an excellent complement to the existing fields on the SSC. **Pierre Francus** (Canada), originally from Belgium, is a professor at the Université du Québec. His broad scientific expertise around quantitative sedimentology, paleoenvironmental reconstruction and quaternary paleoclimatology, fits within the PAGES/CLIVAR, IMAGES, and Polar focus groups.

PAGES science plan

Beyond changes in personnel, 2007 will also see the publication of a new Science and Implementation Plan, which will flesh out PAGES revised scientific structure, the general form of which can be found at www.pages-igbp.org/science/research/newstructure.html. This new plan will provide a framework for activities on and around paleoscience that we hope you will bring to life by getting involved in, as a member or even as a leader.

Next issue of *PAGES News*

The next deadline for manuscript submissions to the PAGES newsletter is 28 February 2007. This issue will contain an open section for your contributions as usual as well as a special section on past human - climate - ecosystem interactions guest edited by John Dearing (UK). Guidelines for submitting articles can be found at www.pages-igbp.org/products/newsletters/instructions.html.

New on the PAGES bookshelf

Indian Monsoon and Climate Variability during the Holocene

Journal of the Geological Society of India special issue, Vol. 68, N°3, September 2006

Guest Editor: R. Shankar, Mangalore University, Mangalagangotri 574199 - India

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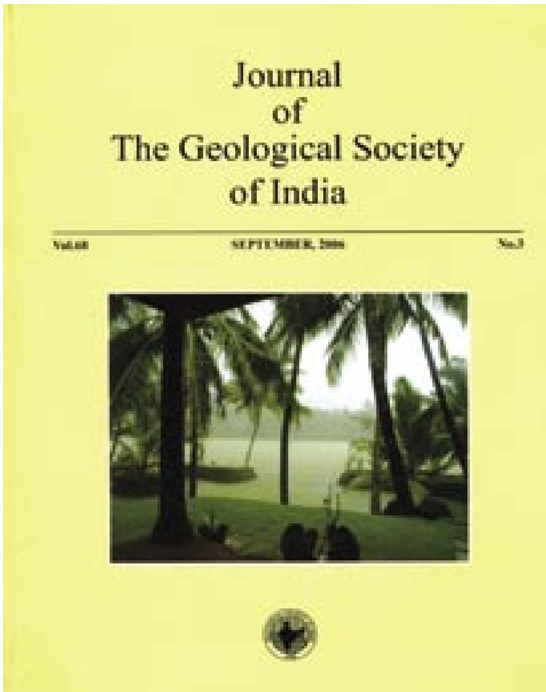
paper abstracts are available at:
www.geosocindia.com/ABSTRACTS/2006/Sept/abst_sept.htm



Contents:

This special issue incorporates 20 papers grouped under four headings: (1) Keynote papers; (2) Paleomonsoon / Paleoclimate from marine records (eight papers); (3) Paleomonsoon / Paleoclimate from continental records (seven papers); and (4) Paleomonsoon / Paleoclimate from other records, modeling and forecasting (four papers). Together, they offer a glimpse of various facets of Indian monsoon and climate during the Holocene.

The Millennium project: European climate of the last millennium

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Millennium is a paleoclimate project funded under the European Union's 6th framework. It was designed by a multidisciplinary consortium of 37 European universities and research institutes and is coordinated by Prof. Danny McCarroll at the University of Wales Swansea, UK. The project aims to address a single question:

- Does the magnitude and rate of 20th Century climate change exceed the natural variability of European climate over the last millennium?

Millennium is developing new proxy-based climate reconstructions from documentary weather records, tree rings, lake sediment cores, peat cores, ice cores, marine sediment cores, and annually banded marine shells. With field sites spread across Europe, reconstructions will be developed at a variety of spatial scales. A modeling component will assess the forcing mechanisms acting upon European climate.

Methodology

There have been many attempts to reconstruct the past climate of the Northern Hemisphere (Esper et al., 2002) and of Europe (Luterbacher et al., 2002), but they produce results that vary, particularly with respect to the longer-term changes. No existing proxy records provide a perfect, unbiased view of past climate, and differences in the way that existing data records have been processed have a strong effect on the reconstructions. Millennium seeks to improve upon this situation with a combination of new proxy records, new analyses of existing records and paleoclimate modeling.

Structure

- Instrumental and documentary archives

Data are being compiled from western, eastern and central Europe, and the Mediterranean. The group is processing derived information into a set of consistent indices expressing variation in temperature and precipitation. Time series are anticipated to be resolved at the monthly level to AD 1500 and at the seasonal level for earlier centuries.

Tree rings

- Paleoclimate information is being extracted from a network of twelve chronologies distributed across Europe from the Iberian Peninsula to the Atlantic margin and polar Arctic. A multi-proxy approach is being used, including ring widths, wood density, stable isotopes of oxygen, hydrogen and carbon, annual height increment, and needle dynamic data.

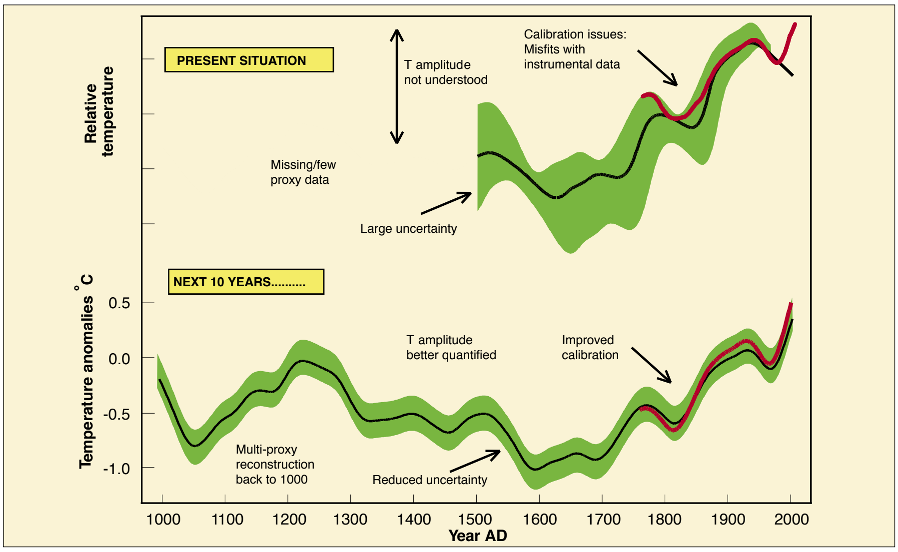

Figure 1: The current limitations of Northern Hemisphere climatology and the advancements into detection and quantitative understanding of European climate variability that Millennium will aim to provide.

- Sediment archives

A multi-proxy approach is being applied to extract paleoclimate information from ice cores, peat deposits and lake sediments. Microfossils, isotope ratios and sediment composition are being analyzed at 11 sites. By carrying out continuous sampling, such that each sample represents as close to annual resolution as it is feasible to obtain, it will be possible to identify short-term abrupt events and pinpoint their date with a high degree of accuracy.

- Marine archives

Sampling has been carried out within Scottish sea lochs and on the North Icelandic Shelf, locations where the rate of sedimentation is high enough to provide a temporal resolution of just a few years. Locations were selected to resolve natural variability in both the position and temperature of the North Atlantic's heat pump. We are also applying dendrochronological methods to the annually banded marine mollusk Arctica islandica to provide a novel way to link high-resolution oceanic records with those on land.

- Data analysis and modeling

When empirical reconstructions of climate records, based on regression techniques (e.g. Mann et al., 1999), are compared with numerical simulations of the past millennium, agreement is achieved only for GCMs that produce climate sensitivities at the low end of the range reported by the IPCC (von Storch, 2004). This poses a dilemma as to whether empirically reconstructed climate records based on regression underestimate variability, or whether the GCMs overestimate sensitivity. Millennium's reconstructions are being developed specifically to reduce the artificial loss of variability at multi-decadal to centennial timescales and allow us to address this dilemma.

Revised and new proxy records will be compared to millennial-scale GCM simulations to derive realistic estimates of sensitivities of differing forcing parameters. Version 3 of the coupled Hadley Centre GCM (HadCM3), and its low resolution equivalent (FAMOUS), will be used for long simulations. We are using distributed volunteer computers over the internet, organized through the ClimatePrediction.net project and welcome international scientific collaboration. Further information is available at www.millennium-project.net.

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Paleoenvironments in south India: Monsoon records from rainfed reservoirs

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Reconstructions of paleoclimates/paleoenvironments in south India have been largely restricted to montane (Sutra 1997), oceanic and mangrove sites (Prabhu et al, 2004, Kumaran et al, 2005). There is very little information from modern and fossil terrestrial sites on the peninsula except for some studies in central India (Chauhan, 2002). This lack is significant from the viewpoint of a regional scale climate or environmental reconstruction. Hence, the focus of our research on the paleoenvironments of south India at the French Institute of Pondicherry (IFP) is to address these data gaps. The questions underlying our research are:

(i) Is it possible to generate pollen data from a network of modern sites, covering diverse vegetation types, distributed over distinct climatic regimes in south India?

(ii) Is it possible to identify suitable terrestrial sites for paleoclimatic reconstruction in this region influenced by the monsoon regimes?

We are currently carrying out two projects to address these questions:

The first project, on modern and fossil pollen studies in the Eastern Ghats, is in partnership with the National Remote Sensing Agency. Remote sensing helps by adding a spatial dimension to the temporal one provided by palynology and geochronology (for which we use radiocarbon and luminescence chronology depending on the site, time interval and sediment record).

The second project, on reconstruction of paleomonsoonal changes using sedimentary records from rainfed irrigation reservoirs (tanks) in south India, is in partnership with Indian Space Research Organization. It aims to ascertain the magnitude and frequency of the southwest and northeast monsoons, to compare recent events with long-term rainfall data in order to generate a calibration curve, to compare sediment records from 3 different monsoon settings (only southwest, only northeast and both southwest and northeast), and to delineate the influence of human activity on the tank systems using remote sensing.

*Figure 1: **Left:** View of a rainfed irrigation tank, with an ancient stone sluice, historically dated to the 5th century. **Middle:** Coring in a tank with a ~ 500 yr history at foothills of Eastern Ghats. **Right**: Trenching at another historical tank with a 13th century stone inscription.*

In the vast geographic area covered in these projects, remote sensing plays a very important role in shortlisting both modern pollen sampling sites and paleosites, namely irrigation tanks or water bodies. From the first short list, historical and archeological records (stone inscriptions) are used to further narrow down the choice to sites that have a well-defined historical date assigned to them, and finally ground truth is essential for selecting a given site for study. With this approach, essentially field-oriented, using a multiproxy research methodology (Anupama et al, 2002) that is inevitably multidisciplinary and incorporating new technologies like remote sensing and the human dimension through history and archaeology, the first phase of our project has succeeded in identifying suitable sites and generating quantitative data. We are currently analyzing these data for a synthesis aimed at delineating both monsoon behavior and human impacts over the last two millennia in south India.

Acknowledgements

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Cosmogenic isotope ^{14}C: Production and carbon cycle

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Global $\Delta^{14}C$ cycle

Radiocarbon is produced by galactic cosmic radiation interacting with atmospheric nitrogen, and enters the global carbon cycle as $^{14}CO_2$, which is well mixed within the atmosphere. Photosynthesis fixes CO_2, and hence $^{14}CO_2$, into plant organic matter and the global food chain. In addition, CO_2 dissolves in water (primarily seawater) to form dissolved inorganic carbon (DIC) that can then be incorporated into marine carbonates. Conventional ^{14}C dating assumes that initial ^{14}C concentration has remained constant. However, atmospheric and surface ocean ^{14}C concentrations have changed notably through time. This is due to changes in either the rate of ^{14}C production in the atmosphere (a function of geomagnetic field intensity and solar variability), or the distribution of ^{14}C between different reservoirs in the global carbon cycle (primarily deep ocean ventilation).

The Earth's geomagnetic field serves to shield the atmosphere from incoming cosmic rays, and when the magnetic field strength increases, ^{14}C production decreases (and vice versa). Similarly, solar wind distorts the Earth's geomagnetic field in a way that reduces ^{14}C production, and a rise in solar activity will cause a decline in ^{14}C production. Records of ^{14}C production variability in the past have been constructed using two primary methods: (1) as a function of past changes in geomagnetic field intensity (Laj et al., 2004) and, (2) by comparison to other cosmogenic nuclides (e.g. ^{10}Be and ^{36}Cl; Muscheler et al., 2005). Over the past 50 kyr, the pattern of changes in ^{14}C production reconstructed using the two methods agree very well (Fig. 1), although the absolute magnitude of ^{14}C production rate is still largely uncertain. The global carbon cycle contains several reservoirs that exchange carbon on timescales relevant to the lifetime of ^{14}C (101-104 years). Within the deep ocean in particular, ^{14}C is sequestered from atmospheric exchange long enough for decay to reduce the deep ocean ^{14}C activity significantly. Changes in the rate of exchange between the deep ocean and the atmosphere, through fluctuations in the meridional overturning circulation (i.e. the North Atlantic component of global thermohaline circulation), can strongly influence atmospheric ^{14}C activity. However, little is known about the detailed spatial and temporal history of deep-ocean ventilation changes and the magnitude of resulting changes in surface-ocean and atmospheric ^{14}C.

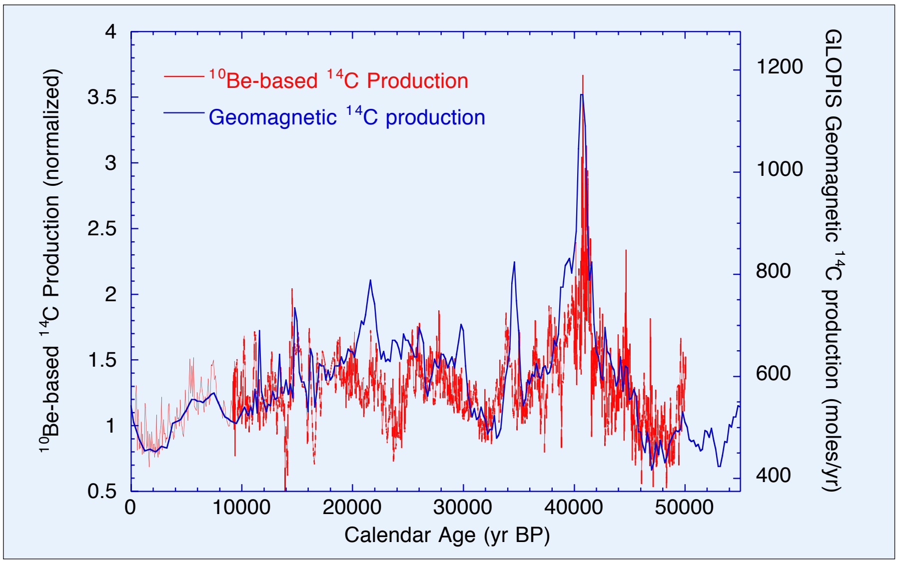

Figure 1: ^{14}C production rate changes from 50 to 0 kyr reconstructed using ^{10}Be flux measured in Greenland ice cores (Muscheler et al., 2005), and as a function of geomagnetic field intensity (Global Paleointensity Stack, Laj et al., 2004; Masarik and Beer, 1999). The two methods show strong agreement in temporal patterns of production change, including distinct peaks associated with the Laschamp and Mono Lake geomagnetic minima.

Observed $\Delta^{14}C$ changes in the past

Recently, marine-based calibration data back to 50 kyr have been provided by ^{14}C- and ^{230}Th-dated corals with irregular sample spacing (Fairbanks et al., 2005; Cutler et al., 2004; Bard et al., 2004), and at higher resolution from marine sediments of the Cariaco Basin (Hughen et al., 2006) and Iberian Margin (Bard et al., 2004). The sediment records show distinct millennial-scale climate variability that can be reliably correlated with Dansgaard-Oeschger (D-O) events in Greenland ice cores and, more recently, ^{230}Th-dated Hulu Cave speleothems. These correlations have been used to transfer the calendar chronologies onto the ^{14}C series in order to provide calibration data sets. Cariaco Basin and Iberian Margin ^{14}C data linked to the ^{230}Th Hulu Cave chronology show excellent agreement with data from ^{230}Th-dated fossil corals back to 33 kyr, and continue to agree despite increased scatter back to 50 kyr (Fig. 2). ^{14}C calibration data independent from a marine-reservoir age-correction have been obtained from a ^{230}Th-dated speleothem on Socotra Island in the Arabian Sea. These data show a close match to the marine sediment and coral ^{14}C records between 40-50 kyr (Fig. 2). The observed convergence of data sets from dispersed archives and geographic locales will likely provide, in the near future, the basis for an extended ^{14}C calibration back to 50 kyr.

Geochemical modeling and global carbon cycle changes

The $\Delta^{14}C$ data reveal highly elevated $\Delta^{14}C$ values during the Glacial period. In order to investigate the implications of the observed $\Delta^{14}C$ record, we use a carbon cycle box model to simulate fluxes between the atmosphere, terrestrial biota plus soil/detritus, surface and deep oceans, and shallow and deep marine sediments containing organic and inorganic carbon. Reservoir inventories and rates of exchange are specified from consensus estimates for the modern (pre-industrial) carbon cycle (Hughen et al., 2004). ^{14}C production rates are calculated as a function of geomagnetic field intensity (Laj et al., 2004), with a contemporary ^{14}C production rate of 2.02 atom cm-2 sec-1 (Masarik and Beer; 1999). As noted previously, however, this ^{14}C production rate exceeds the observed sum of ^{14}C in active reservoirs. A constant scaling factor is therefore applied to the production rates in order to tune the model reservoir $\Delta^{14}C$ values at model year 0 to observed modern values (Atmosphere 0‰, Terrestrial Biosphere -5‰, Surface Ocean -53‰, Deep Ocean -159‰). A model simulation with fixed modern exchanges ("full carbon cycle") but variable ^{14}C production rate produces a temporal pattern of $\Delta^{14}C$ change similar to paleo-observations, and matches the magnitude of $\Delta^{14}C$ change particularly during the Holocene (Fig. 2). However, the simulation produces maximum $\Delta^{14}C$ of only ~300‰ for the interval 20-40 kyr, whereas observed $\Delta^{14}C$ exceeds the simulated changes by as much as ~400‰, most prominently around ~30 and ~40 kyr.

In this simple model, reducing the surface-to-deep-ocean exchange produces an additional atmospheric and surface ocean

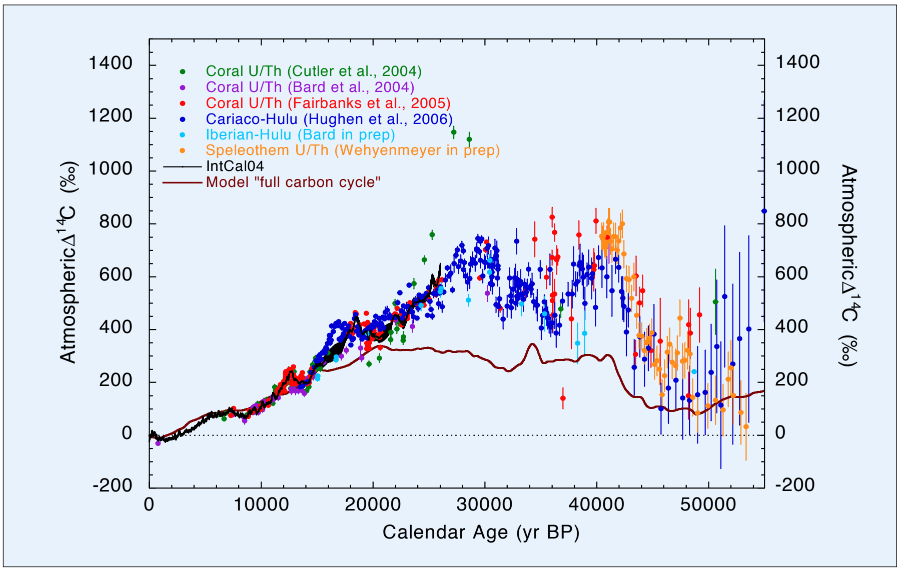

Figure 2: ^{14}C activity ($\Delta^{14}C$) data for the past 50,000 years. IntCal04 is shown back to its limit of 26 kyr. Marine coral and sediment ^{14}C data have been corrected with a constant reservoir age, and speleothem data have been corrected with a constant dead carbon fraction. The paleo-$\Delta^{14}C$ observations are plotted compared to a carbon cycle box model simulation representing fixed preindustrial boundary conditions and changing ^{14}C production ("full carbon cycle"). Error bars show 1-σ $\Delta^{14}C$ uncertainty.

$\Delta^{14}C$ response of ~200‰, encompassing most of the Glacial age data. Reducing flux to shallow sediment reservoirs is required to match the highest observed $\Delta^{14}C$ values. According to the model, however, the prescribed change in surface-to-deep-ocean exchange would produce a doubling of the surface-to-deep-ocean $\Delta^{14}C$ difference. Observations do provide some evidence of decreased Glacial $\Delta^{14}C$ in the deep western and eastern North Atlantic, as well as deep eastern equatorial and southwest Pacific (for review see Hughen et al., 2006). However, such a large change in Glacial deep ocean $\Delta^{14}C$ has not been observed in the western equatorial Pacific (e.g. Broecker et al., 2004). It is important to note that most of the paleo-ocean $\Delta^{14}C$ reconstructions correspond to the period around the Last Glacial Maximum (~21 kyr BP), an interval when the simulated $\Delta^{14}C$ response to production rate changes alone is close to the observations (especially if reasonable production rate uncertainties are considered). Another serious issue is that reconstructed rates of $\Delta^{14}C$ change at the beginning of the last deglaciation, ~17 kyr, are too large to be explained by changes in production rate alone and require a substantial dilution of ^{14}C atoms in the atmosphere by a more depleted reservoir. Reconstructions of transient deglacial $\Delta^{14}C$ changes in the intermediate depth western and deep eastern North Atlantic are consistent with a major reorganization of deep ocean circulation at that time, probably involving increased ventilation of a previously isolated deep water mass of southern or Pacific origin (e.g. Adkins et al., 2002). These model simulations can place constraints on the magnitude of deep ocean $\Delta^{14}C$ anomalies required to explain the surface marine record. In addition, the model data make quantitative predictions of the increase in surface marine reservoir age during the Glacial period. Unfortunately, however, observations of Glacial reservoir variability from low-latitude sites are rare. More sophisticated model simulations with increased spatial resolution would help identify the patterns of increase in reservoir age according to latitude and ocean basin. Regardless, it is clear that high-quality observations are needed from each of the three principal carbon reservoirs—atmosphere, surface and deep ocean—in order to constrain changes in both deep ocean $\Delta^{14}C$ and surface marine reservoir age, and to understand the history of radiocarbon and global carbon cycle changes.

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For full references please consult:
www.pages-igbp.org/products/newsletters/ref2006_3.html

Assuring measurement quality: The international ^{14}C laboratory inter-comparison program

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Introduction

In order to achieve reliable, precise and accurate ^{14}C age measurements, laboratories routinely undertake both formal and informal quality assurance programs. Such programs may involve the repeated and routine measurement of an internal standard (such as a bulk cellulose sample), the results of which enable the laboratory to evaluate their reliability and precision. They may also routinely have access to known-age material against which to assess their accuracy. Beyond this, however, many laboratories regularly participate in inter-laboratory comparisons to provide independent checks on laboratory performance.

Reference material for ^{14}C calibration

High-quality ^{14}C measurements also require traceability to international standards whose ^{14}C-activities are known exactly by independent means, and also to reference materials whose activities are estimated and typically accompanied by associated uncertainty statements. Within the ^{14}C community, there has been an increasing realization of the need for adequate reference materials and a resultant development of both internal and external quality assurance (QA) procedures. Routinely, ^{14}C laboratories make use of a number of standards and reference materials whose activities are known or are estimated from large numbers of measurements made by many laboratories (e.g. NIST OxI, OxII, IAEA C1-C8). More recent ^{14}C inter-comparisons have also created a further series of natural reference materials (Scott, 2003, Scott et al, in prep).

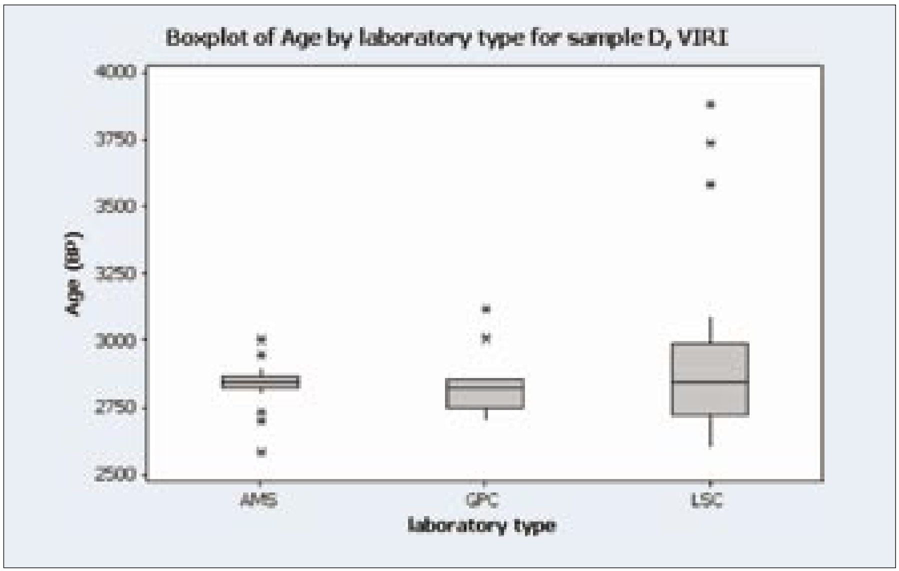

*Figure 1: Boxplot showing the distribution of results for a charred grain sample (sample D, VIRI) for the three laboratory types (32 AMS, 31 LSC and 10 GPC). The boxplot represents the median, lower and upper quartile and minimum and maximum. An * identifies an outlier. The lower quartile is the value below which 25% of the results lie.*

History of inter-comparisons

Since the early days of applied ^{14}C measurement, it has been common practice for laboratories to exchange samples in attempts to improve and sustain analytical confidence. With time, this practice has given way to a succession of more formal inter-comparison exercises. Within the ^{14}C community in the past 20 years, there have been a number of very extensive inter-laboratory trials. These comparisons have varied widely in terms of sample type and preparation, with their primary goal the investigation of the comparability of results produced under possibly quite different laboratory protocols. Regular comparisons have reassured users that the laboratories are striving to ensure highest quality results, while at the same time allowing the laboratories to identify any systematic offsets and additional sources of variation. Thus, participation in a laboratory inter-comparison has become an important part of a formal QA program.

Here we summarize some of the findings from the two most recent ^{14}C inter-comparison exercises (FIRI (Fourth) and VIRI (Fifth), Scott 2003 and Scott et al, in prep.). VIRI is ongoing at this time but continues the tradition of TIRI (Third) and FIRI, operating as an independent check on laboratory procedures. It is a 4-year project, with the first phase already completed. Phase 2, using bone samples, is due to be reported by the end of 2006. Further stages will include samples of peat, wood and shell with a range of ages. VIRI, like the TIRI and FIRI inter-comparisons, is a ^{14}C community project, with samples provided by participants and a substantial laboratory participation rate of over 75%.

What questions have been asked and answered by these inter-comparisons?

- Comparability of measurements from different laboratories

One of the main questions that such inter-comparisons are used to answer concerns how comparable the results are among laboratories, especially where some use different procedures and techniques. For the ^{14}C dating community, this historically concerned the comparability of results from the accelerator mass spectrometric (AMS) and radiometric (liquid scintillation (LSC) or gas proportional counting (GPC)) laboratories.

From FIRI, overall and on average, no evidence of significant differences in the results between AMS, GPC and LSC laboratories was found. In the first phase of VIRI, a similar preliminary conclusion was drawn (Scott et al, in prep.). Figure 1 below shows the distribution of results for sample D (charred grain) in VIRI.

- Variation

Clearly the results among laboratories do vary, but an inter-comparison exercise can assess the degree of variation and also which factors might explain such variation (aside from simply random fluctuations). One aspect of variation concerns outliers, or extreme observations. In FIRI, roughly 10% of the total results were identified as outliers (which is around twice as frequent as would be expected). An outlier is an observation which is either too young or too old, defined statistically as those values that are greater than 3 inter-quartile ranges from the nearest of either the lower or upper quartiles. The distribution of outliers was not homogeneous across the laboratories, with the majority of outliers coming from around only 14% of the laboratories.

Can we identify any reasons for the variation in results? Modern standard and background material used were studied but no evidence was found that these factors made a significant contribution to the overall variation. The type of modern standard used, however, did seem associated with the outlier distribution.

- Accuracy

Accuracy is concerned with the 'correctness of the result' and refers to the deviation (difference) of the measured value from the 'true' value. Ideally with known-age samples, this can be independently estimated and a small number of known-age samples have been included (typically dendrochronologically dated wood). However, more commonly, we must assume that we

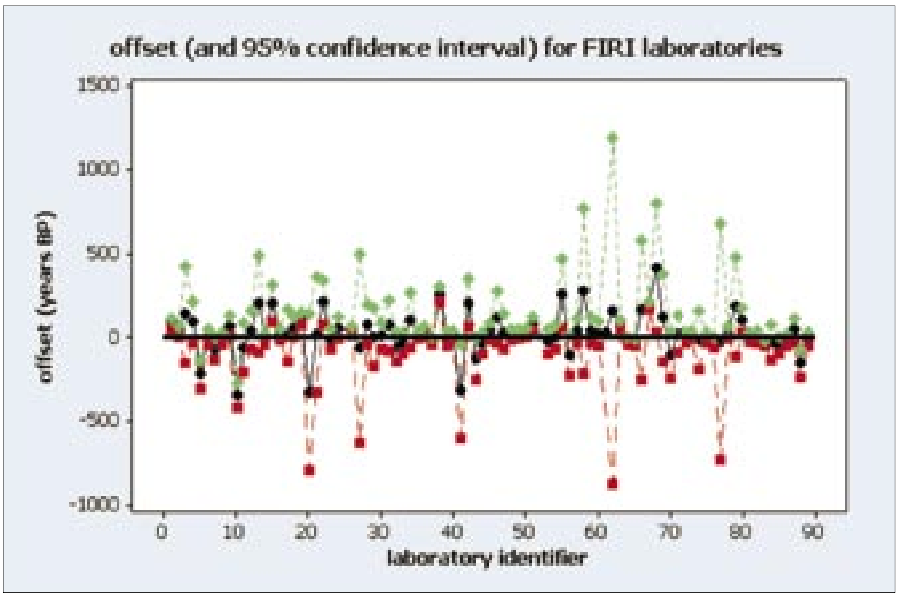

Figure 2: Offset (and 95% confidence interval) for dendrochronologically dated samples (3200-3239 BC, 3299 - 3257 BC and 313-294 BC) showing the upper (green diamonds) and lower (red squares) limits of the 95% confidence interval, and the point estimates of the laboratory offsets (black circles).

can define (through calculation) what the 'true' ^{14}C age will be (the consensus value) and then we can estimate for each laboratory, whether there is a constant offset (or a bias) from this consensus. The current program of inter-laboratory comparisons has afforded an opportunity for laboratories to assess their accuracy. In each inter-comparison, the consensus values for the unknown age samples was calculated and reported. Figure 2, , shows the offset (and 95% confidence interval) for individual laboratories based on the dendrochronologically dated samples included in FIRI. The sample dendro-ages were 3200-3239 BC, 3299 - 3257 BC and 313-294 BC.

Conclusions

Analyses of results from FIRI and phase 1 of VIRI support the fact that radiocarbon laboratories are generally accurate and precise. The results from FIRI are significant in that they show broad agreement between measurements made in different laboratories on a wide range of materials, and they also demonstrate no statistically significant difference between measurements made by radiometric or AMS techniques. As a result of the inter-comparison program, an extensive suite of natural reference materials (such as wood, carbonate, etc) spanning the applied ^{14}C timescale has been created by the ^{14}C dating community. These can now be used by ^{14}C labs to improve their dating accuracy and are thus of great benefit to the users of ^{14}C dates.

Acknowledgements

FIRI and VIRI are supported by EC FPIV programme and English Heritage. The assistance of sample providers is gratefully acknowledged, in addition to the support of all participating labs.

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IntCal and the future of radiocarbon calibration

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Background

In addition to being crucial to many archaeological studies, radiocarbon ages form the chronological basis for many Holocene and late Pleistocene paleoclimatic studies and paleoenvironmental reconstructions. The basic radiocarbon age calculation assumption of constant atmospheric ^{14}C content is not valid, however, due to solar- and geomagnetic-induced changes in production rate and ocean circulation changes. In order to compare radiocarbon chronologies with those derived from other means, such as ice core or U/Th dated sequences, it is necessary to calibrate against measurements of "known" age samples.

Calibration curves were originally based only on ^{14}C measurements of known-age tree-rings and a calibration curve for Holocene marine samples was constructed using the atmospheric data as input into a simple ocean-atmosphere box diffusion model. More recently, marine records, U-Th dated corals and foraminifera from varve-counted sediments of Cariaco Basin, combined with reservoir corrections, provide high-resolution atmospheric calibration beyond the range of the tree-ring record. The ocean-atmosphere box diffusion box model, however, is used for Holocene marine calibration where marine calibration data are generally not available with sufficient resolution and precision. After a disastrous start of multiple independent "calibration" data sets that yielded disparate calendar ages

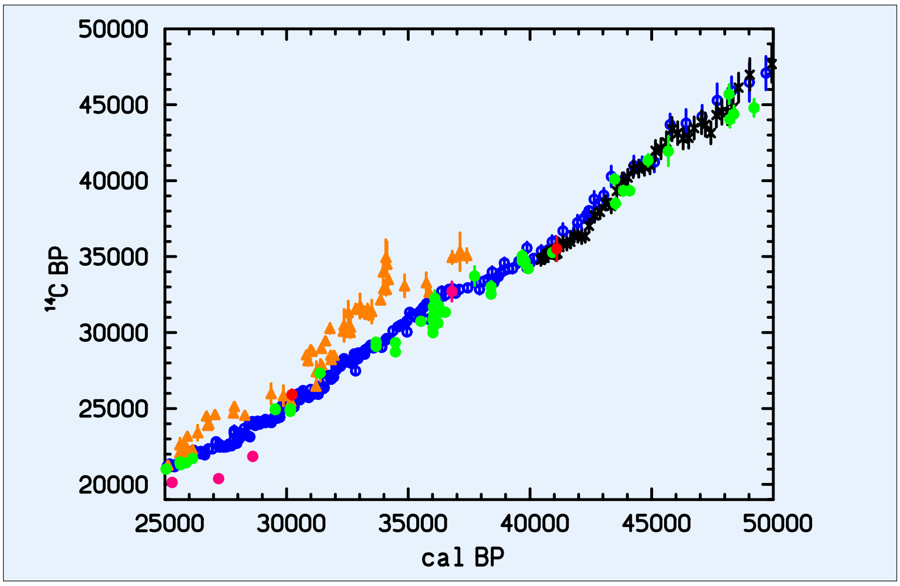

Figure 1: Selected ^{14}C data sets >26 cal kyr BP with calendar timescales based on U/Th dating, varve counts or through correlation to U/Th-dated speleothems. The marine and speleothem records are corrected with a constant reservoir or dead carbon fraction offset as specified in the original publication. Uncertainty is shown in the ^{14}C ages only as one standard deviation. Corals are given as solid circles: red (Bard et al., 2004); pink (Cutler et al., 2004); green (Fairbanks et al., 2005). The Cariaco Basin foraminifera data with the timescale from the correlation to the Hulu Cave is given as open blue circles (Hughen et al., 2006), Lake Suigetsu macrofossils as solid orange triangles (Kitagawa and van der Plicht, 2000), and Arabian Sea speleothem as black crosses (Weyhenmeyer et al., 2003).

and confusion among users, radiocarbon calibration curves have been constructed by small groups utilizing the best available and reproducible data sets, and ratified by the attendees at the International Radiocarbon Conferences. As the types of records available for calibration have diversified and the pros and cons of each realized, a larger, more formalized group has become a necessity. In 2002, the IntCal Working Group was created and has since met at a series of workshops funded by the Leverhulme Trust. The IntCal group has produced estimates of the calibration curves for the main carbon reservoirs: the Northern Hemisphere atmosphere (IntCal04), the Southern Hemisphere atmosphere (SHCal04), and the marine environment (Marine04). SHCal04 was the first ratified calibration curve for the Southern Hemisphere.

Most of the early calibration curves were constructed from a simple weighted average of all data within a 10- or 20-year bin. This ignored the uncertainty in the calendar axis, which can be significant for some records (non-tree-ring in particular). For the 2004 curves, Buck and Blackwell (2004) devised a tailor-made curve estimation method based on a random walk model (RWM), which takes account of the uncertainty in both the calendar ages and radiocarbon determinations that make up the raw calibration data, and formally acknowledges the covariance of the data points (induced by the fact that they all derive from the same underlying radiocarbon production mechanisms).

When the IntCal Working Group compiled the 2004 calibration data sets, many types of records were considered, including U/Th dated corals, speleothems with U/Th age models, macrofossils from varved lake sediments, and foraminifera from varved and non-varved marine sediments with calendar age estimates (based on correlations to ice core records). Despite reasonably good agreement between many of these records beyond the range of the tree-ring data, however, only the corals and the foraminifera from the varved sediments were considered to meet the IntCal criteria for calibration back to 26 cal kyr BP (0 cal BP = AD 1950). As a result of these uncertainties, the group chose not to produce a calibration curve for this time period; instead a modeled estimate of the curve underlying all the data sets was determined and called NotCal04 to signify that it was NOT of calibration quality. Because of the lack of an internationally ratified calibration curve beyond 26 cal kyr BP, however, there has been a proliferation of "calibrations" based on individual data sets or selected compilations. Although such comparisons are valuable research tools for exploring possible leads and lags in the various carbon reservoirs and for providing tentative calendar age estimates, the mixed approaches make it difficult to compare records with different age estimates and, unfortunately, have the potential for causing significant uncertainty across the scientific and archeological community.

The task ahead

New and/or improved ^{14}C data sets for the time period beyond 26 cal kyr BP were reported at the 19th International Radiocarbon Conference in Oxford (April 2006) and are generally in good agreement. Attendees of the conference business meeting agreed that the IntCal Working Group compile a standard "calibration" data set for the entire range of radiocarbon (<55 kyr BP). Due to the rapid progress in the production of ^{14}C calibration data sets, the Radiocarbon community expressed the need for annual updates to the curves beyond the end of IntCal04 (currently at 26 cal kyr BP). These curves would provide tentative calendar age estimates and would be distinct from the explicitly higher-quality, tree-ring calibration data, and not ratified in a similar fashion to the IntCal curves. Ideally, data sets beyond 26 cal kyr BP should be referred to as 'comparison curves' until a 'calibration curve' is ratified. The NotCal04 estimate relied on modeling the (sometimes quite large) offsets between data sets using a random effect component, which we hope not to need for the next (non-ratified) output.

In order to provide more transparency and wider community input, an Oversight Committee including experts in a number of fields will be selected on the basis of online voting to be handled by the Radiocarbon journal. Funding is currently being sought for an IntCal Working Group meeting, including the Oversight Committee, to review and recommend the data to be included in the next IntCal extension, as well as for research assistance.

In addition, the current internationally ratified calibration curve, IntCal04, is due for a full update when the floating tree-ring extension from Germany and Switzerland are linked. This work is being undertaken through an ESF-EuroClimate grant to research groups in Heidelberg, Aix-en-Provence, Budapest, Lund, Stockholm, Stuttgart-Hohenheim and Zurich, and is expected to be completed by 2007-8. If the estimated linkage of the floating tree-ring chronology is correct, then the calibration results of terrestrial radiocarbon dates from the end of the last glaciation to the beginning of the Younger Dryas chronozone will be significantly different from those derived from calibration using IntCal04.

It is anticipated that terrestrial records, such as the floating kauri tree-rings or terrestrial macrofossils from the new Lake Suigetsu cores, will eventually provide a terrestrial radiocarbon calibration to 55 kyr with the detail necessary to resolve leads and lags in the climate system, or distinguish cause and effect of landscape changes related to early human occupation (e.g. of Australia). This cannot be achieved with the naturally smoothed marine and speleothem records (Fig. 1). In the meantime, terrestrial radiocarbon calibration or comparison curves beyond the end of the known-age tree-ring record will need to be constructed primarily from marine-based archives such as corals or foraminifera. The spatial and temporal variability of marine radiocarbon reservoir ages (MRA) is therefore an outstanding problem (c.f. Reimer & Reimer; this issue). A corollary is also present in speleothem-based records, which have to make assumptions on the constancy or model-estimate of the dead carbon fraction.

It has been suggested that coupled ocean-atmosphere global circulation models (OGCMs) could provide some insight into past MRA. However, OGCMs have a difficult time accurately recreating the spatial distribution and pattern of natural and bomb ^{14}C in the ocean. Thus, these model simulations should not be thought of as the solution to estimate past reservoir age variations at present but more in terms of sensitivity experiments towards potential solutions. An updated and extended event stratigraphy approach such as that used by Bjorck et al. (2003), as well as further paleo-reservoir age measurements, where appropriate sequences exist, should be undertaken.

And finally: semantics. What should we call the tentative calendar age curves and the resulting estimates? There needs to be some short but easily understood abbreviation so that one can readily tell true calibrated radiocarbon ages (derived from the use of internationally agreed radiocarbon calibration curves) from more tentative calendar age estimates derived from the use of an interim curve based on a non-ratified compilation of potential calibration data.

Despite these uncertainties, if all goes well, radiocarbon users can expect an updated IntCal04 and a new compilation curve for calendar age estimation back to 55 kyr BP in the near future. There are exciting times ahead.

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The potential for extending Intcal04 using OIS-3 New Zealand sub-fossil Kauri

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Introduction

Recent articles by Turney et al. (2006) and Balter (2006) publicized the current state of radiocarbon calibration beyond 20 kyr BP. They stress the need for new calibration studies, which are critical for developing late Pleistocene chronologies for paleoclimate and archeological research. Peat bogs in Northland, New Zealand contain large numbers of sub-fossil kauri (Agathis australis) logs in discontinuous sequences ranging in age from a few hundred years to more than 60 kyr BP. The buried trees are well preserved, often with their bark still attached and one has been found to contain more than 2000 rings. This article summarizes some current research being undertaken on the Northland sub-fossil Oxygen Isotope Stage (OIS)-3 (25 – 60 kyr BP) kauri resource by a team from New Zealand, Australia and the UK.

Sampling

OIS-3 "ancient kauri" logs are found in bogs scattered over a 300 km stretch of northern New Zealand, from about 34°50′ to 36°20′S (Palmer et al., 2006). Kauri is a highly valued timber species but past over-exploitation of living stands now means supplies are limited. The remarkable preservation state of the buried kauri and its inherent value has meant the wood is being harvested for commercial purposes. Our practice has been to take advantage of this and work alongside milling companies who use large earth moving machinery to mine the buried logs.

As the logs are extracted, we cut cross-sections from the base of the bole but above the root plate to avoid tree-ring distortion because of buttressing and flaring. Tree-ring samples are prepared and analyzed following well-documented dendrochronological techniques for ring-width measurement and cross-dating.

Dendrochronological analysis

Thus far, we have collected 167 cross-sections from 16 different pre-Holocene bog sites and 145 have been measured (Palmer et al., 2006). Several discontinuous floating chronologies have now been developed which in total span more than 10,000 years. The preliminary cross-dating has shown that it is possible to cross-match between different trees from different locations (i.e. inter-site cross-matching). Furthermore, the spread in the radiocarbon ages obtained from within and between sites indicates that preservation did not take place during only one specific period of time. A possibility therefore exists for the development of long continuous sections of chronology within OIS–3.

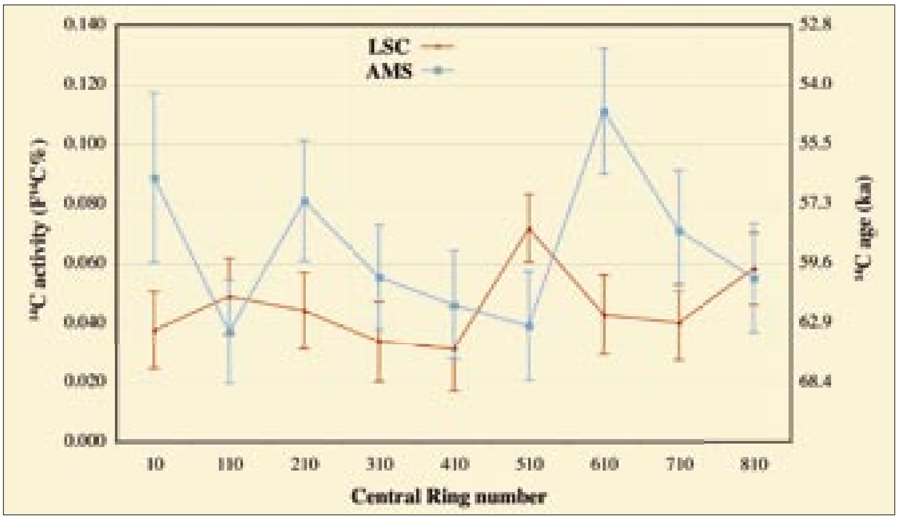

Figure 1: ^{14}C activities (F14C%) for nine consecutive 100-ring blocks extracted from Vinac Farm, tree 6, by both LSC and AMS (data from Hogg et al., accepted).

Radiocarbon dating

As with many paleoecological studies, radiocarbon dating has been critical to understanding the relative time periods covered by the different tree-ring series. Integral to radiocarbon dating OIS-3 wood is the need to achieve reproducible, low-activity radiocarbon blanks and a robust, transparent methodology for assigning standard errors to ^{14}C ages that are close to the limit of the method. Although finite radiocarbon ages on organic carbon samples beyond 50 kyr BP are becoming more common in the literature, few attempts have been made to demonstrate their accuracy or precision. We have established a robust methodology, permitting accurate and reproducible ^{14}C dates in the 50-60 kyr BP age range, by both high-sensitivity liquid scintillation counting (LSC) and accelerator mass spectrometry (AMS) methods (Hogg et al., submitted; Hogg et al., accepted; Turney et al., accepted).

The reproducibility of these methods can be seen in Figure 1. The graph shows ^{14}C activities for 9 consecutive 100-ring blocks of wood extracted from a sub-fossil kauri log (mean age of ca. 61 kyr BP) close to background age.

Of the 16 sub-fossil (pre-Holocene) kauri sites, 7 have returned finite radiocarbon ages from the α-cellulose wood fraction spanning the full range of OIS-3 (Fig. 2). Ages of 24.9 kyr BP, 27.8 kyr BP (Finlayson Farm) and 28.5 kyr BP (Omaha Flats) indicate that stands of kauri are preserved at the end of OIS-3 and the transition into OIS-2. In contrast, material obtained from sites such as Trig Rd (62.2 kyr) demonstrates that trees are available towards the limits of radiocarbon dating and towards the transition into OIS-4. In between these extreme dates, we have identified trees that fall throughout OIS-3, suggesting that climatic and environmental conditions were suitable for preserving material during this time period.

Conclusions

The determination of a reliable, calibrated timescale encompassing the full range of the radiocarbon dating method is crucial if we are to understand fully the mechanisms of climatic, archeological and environmental change through the last glacial period. Unfortunately, however, there is no internationally accepted radiocarbon calibration curve beyond 26 kyr BP, largely due to inherent problems with the materials used. Ideally, dendrochronologically dated sub-fossil trees can provide annually resolved samples on an absolute timescale, with the

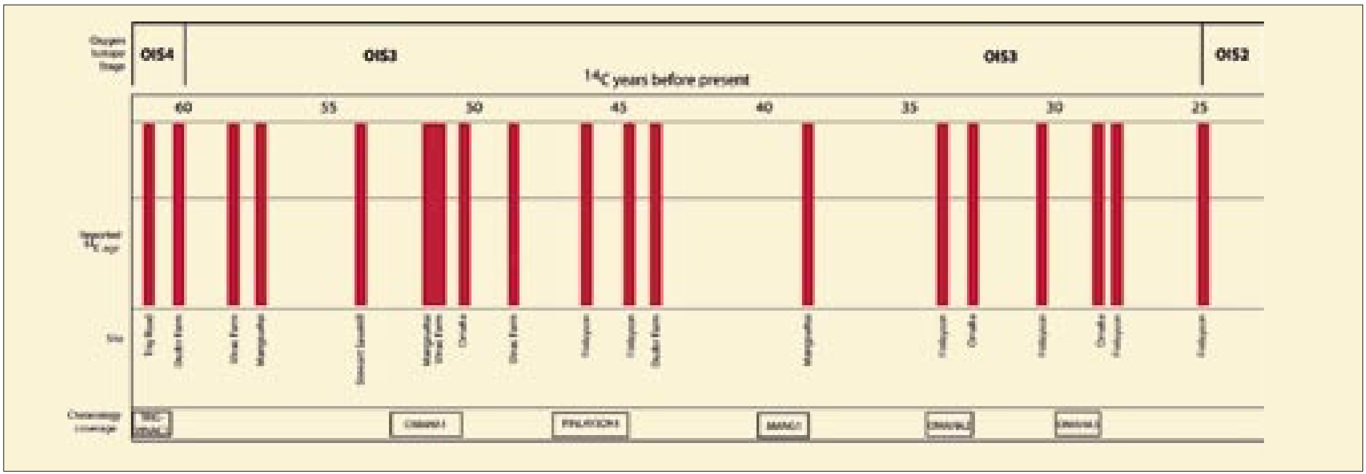

Figure 2: Chronologies and distribution of finite a-cellulose ^{14}C ages obtained on sub-fossil Agathis australis (Northland, New Zealand) – modified from Turney et al., accepted).

additional assurance that their carbon content is truly representative of atmospheric CO_2 at the time of growth. The principal sources of uncertainty that have plagued other attempts at calibration in this time range are thereby avoided. We have shown the considerable potential of New Zealand kauri (Agathis australis) for developing long floating sections of calibration curve in the time period 26-60 kyr BP and the LSC and AMS techniques that are required to obtain precise and reproducible ages at these older time periods. It must be remembered that IntCal04 teams took approx. 30 years to build 26,000 years of chronology. Although significant progress has been made with the kauri, a considerable investment in both time and resources will be necessary if this enormous task is to be completed.

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Marine reservoir corrections and the calibration curve

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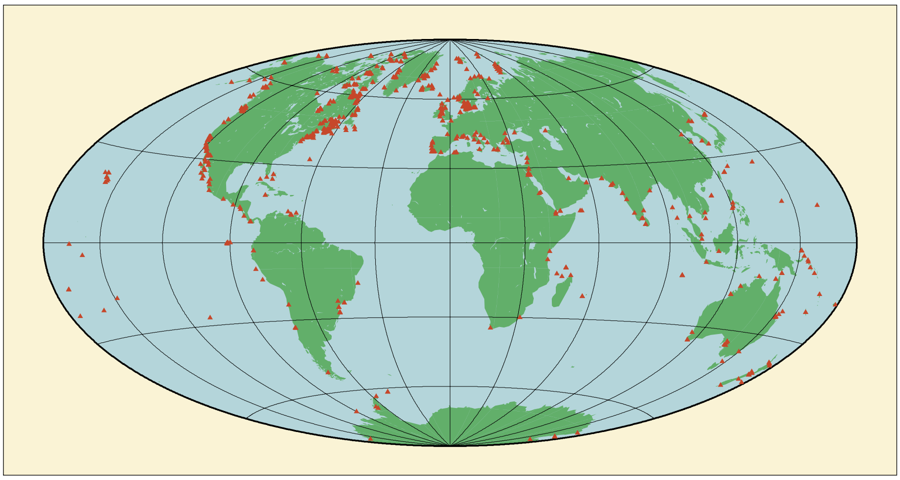

Figure 1: Locations of ΔR values in the Marine Reservoir Correction Database; http://calib.org/marine.

The surface ocean carbon reservoir is variable both spatially and temporally, causing calibration of radiocarbon dates of organisms that have taken up marine carbon to be fraught with uncertainty. The paucity of reservoir age data that existed in 1993 on the publication of the seminal paper on the technique (Stuiver and Braziunas, 1993) has been alleviated to some extent. The largest archive of published ΔR data, which is located at http://calib.org/marine, now contains more than 800 entries (Fig. 1). However, these data are of varying usefulness in determining the apparent age of the ocean water where they were collected. The following paragraphs will outline the considerations to make in combining, or averaging, available data to form a ΔR estimate for a particular locality, focusing initially on Holocene samples for which modern day ΔR are likely to be valid. Recommendations for the improvement of data quality will be made, followed by a discussion of how time variability should be incorporated in ΔR values.

ΔR is calculated by obtaining independent calendar and radiocarbon ages for an organism that has sampled marine carbon. The most straightforward method to obtain the calendar age is to ascertain the year of death of the organism from historical records. It may also be obtained by carbon dating a terrestrial sample that can be unambiguously paired with a marine sample. Modern (post bomb) samples are avoided for this purpose because the distribution and ocean uptake of ^{14}C derived from atmospheric weapons testing is highly variable. Once the cal age is known, it is used to look up a ^{14}C age in the 'global' marine calibration curve. The difference between this ^{14}C age and the measured ^{14}C age of the marine sample is defined as ΔR. A Bayesian technique that relaxes the contemporaneity requirement between the terrestrial and marine samples has been developed (Jones and Nicholls, 2002) to quantify uncertainty in the match up of the calendar ages of the paired samples.

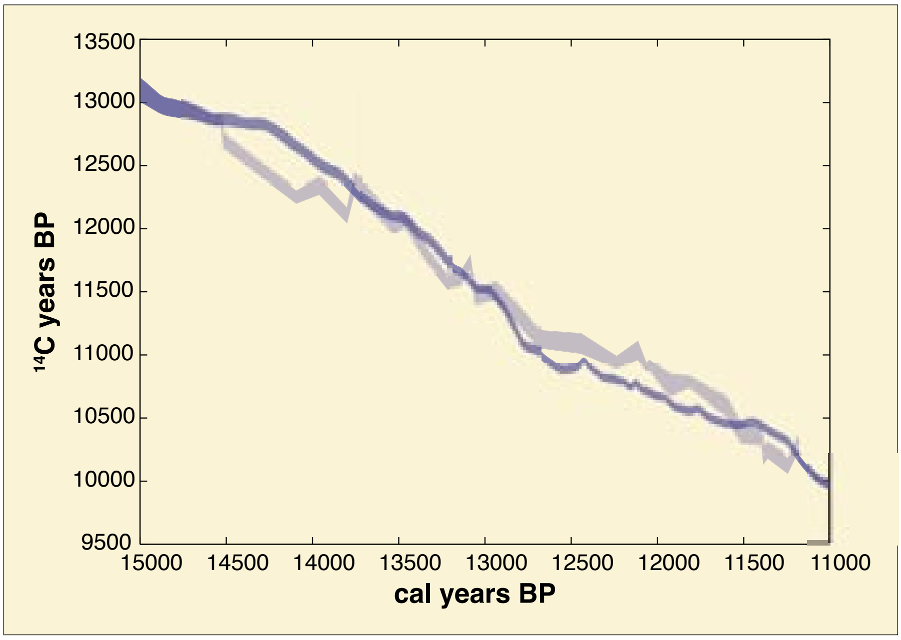

Figure 2: An example of a "curve snippet" derived from measurements by Bondevik et al. (2006) shown with the Marine04 curve in the dark color for comparison.

Before published ΔR data is accepted for consideration, an assessment must be made of whether the organism that was used to determine ΔR took up dead carbon in its lifetime, as for example, gastropods may do. A known value of ΔR may be unusable for general marine calibration purposes if the dated material was influenced by carbonates or other sources of old carbon taken up during the organism's feeding process. Difficulty may also arise if the ΔR is derived from a scavenger that has made a diet of animals that take up old carbon. In this case, a determination must be made of whether the old carbon is taken into its soft body tissue or only into the shell. The ΔR database at the calib.org website was recently expanded to contain dietary preferences of the dated material but much work remains to be done in populating these fields with data. The participation of a biologist would greatly help in identifying database records that are suspect due to old carbon influence. The problem acquires an additional dimension when realizing that bottom-scraping feeders may be suitable indicators of ocean age if there are no carbonates in their habitat, or if the sample needing calibration is of the same species in the same environment.

Generally, ΔR is not available at the precise location of the sample in question, so an estimate must be made of which nearby ΔR values are most likely suitable for inclusion. This requires knowledge of local ocean currents. Ideally, only ΔR values that are from the precise location or 'upstream' of the site in question should be used. Recently, a compilation of known regional ocean-current information was begun at http://calib.org/marine. Presumably, far more information is available and it is only a question of transfer of knowledge from the oceanography to the radiocarbon community.

When all these considerations have been made, the selected ΔR values need to be combined into a weighted average. This produces an estimate of the uncertainty of ΔR, which must seem amazingly low to anyone who has undertaken an assessment of all the contributing uncertainties! The problem is that there is no way to quantify uncertainties in diet, habitat, and ocean currents, particularly using pre-bomb samples collected for entirely different purposes. However, by selecting the appropriate species, where possible, and using the standard deviation rather than the uncertainty on the mean, at least some of the variability is accounted for.

So far, the discussion has focused on the dating of Holocene samples, during which time it can often be assumed that little change in major ocean circulation occurred. This is not strictly true, of course, as regions where there is upwelling of deep ocean water have shown significant differences in ΔR during the Holocene (Soares and Dias, 2006). During the last glaciation and termination, however, there were potentially larger and more widespread changes (Bondevik et al., 2006; Sarnthein and Grootes, 2006; Grootes and Sarnthein, this issue). The problem of temporal variability in the marine reservoir age also enters into the construction of the marine calibration curve itself. The procedure for constructing this curve from multiple data sets involves correcting each data set to a global value and then determining the average offset of that curve from the atmospheric curve. Different versions of IntCal have used different values for this offset, depending on the state of knowledge at the time the curve was constructed. Future versions of IntCal will need to reflect the knowledge we have gained of the time variability of the reservoir age.

We now present a recommendation for dealing with time dependence of ΔR during calibration. This problem has been addressed in the literature (Deo et al., 2004) but generally in an ad hoc fashion. We propose that a Bayesian offset model, similar to the one developed for the Southern Hemisphere calibration curve (Buck and Blackwell, 2004), be developed for ΔR. The model would use ΔR values available through time to generate a varying offset from the marine calibration curve. During time periods when ΔR is not time dependent, the offset model would produce a smooth transition into the marine curve plus constant ΔR. The ΔR database at calib.org would be modified so that 'curve snippets' would become part of the data record, and calibration programs would have to be modified to use these snippets (Fig. 2). This approach represents a step away from the current paradigm of a constant regional ΔR value applied to a global curve, and effectively introduces regional calibration curves. However, it deals effectively with the problem of a calibration that extends beyond the time period of which we have knowledge of ΔR variability, and falls back to the global baseline marine calibration.

http://calib.org/marine is currently hosted and maintained by the ^{14}CHRONO Centre at Queens University Belfast, Belfast, Northern Ireland.

Note

Data used in this study is available at:
http://calib.org/marine

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New approaches to constructing age models: OxCal4

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Introduction

When looking at past changes in the climate and their impact on the environment, timing is all-important. This is not so much because we want to know exactly when something happened but because we want to know how fast and in what order the changes occurred. For this reason, very well dated records, such as ice-cores, play a major role in our understanding of past climate. For most environmental records we need to make use of less precise dating methods, such as radiocarbon or Uranium series, sometimes in conjunction with relative dating information from varves or deposition-rate models. In order to improve overall dating precision, assumptions are also sometimes made about the synchronous nature of climate change—assumptions that can result in circular reasoning when we come to interpret the results.

Age models with uncertainties

It is an unfortunate fact that once we put together a lot of information from different sources, we introduce considerable uncertainties in our age estimates. This is particularly true in the case of radiocarbon dating, where the calibration process results in complex probability distributions that are frequently multimodal. In order to get back to something that is easier to deal with, simple best-fit age models are often applied. However, while this approach may be useful for putting a record roughly onto an absolute timescale, it is not good enough if we wish to compare the timing of events between records with good accuracy and precision. To do so, we need ways of estimating our uncertainties in age at all points in the records and to recover as much relative date information as possible.

For these reasons there has been increasing interest in methods for combining information from different sources. For over a decade now, such approaches have been used in archeological studies where we frequently have relative date information and increasingly these methods are being used in other disciplines (Buck and Millard, 2004). This is in part due to the widespread availability of software such as OxCal (Bronk Ramsey, 1995), BCal (Buck et al., 1999) and DateLab (Jones and Nicholls, 2002) for performing such analyses. In recent years, such methods have also been applied to deposition models, particularly for peat (see for example Blaauw and Christen, 2005). At the 19th international radiocarbon conference held in Oxford in April 2006 (http://c14.arch.ox.ac.uk/conference.html) there were several papers presented on developments in age-depth modeling, including the new age-depth models included in the OxCal program.

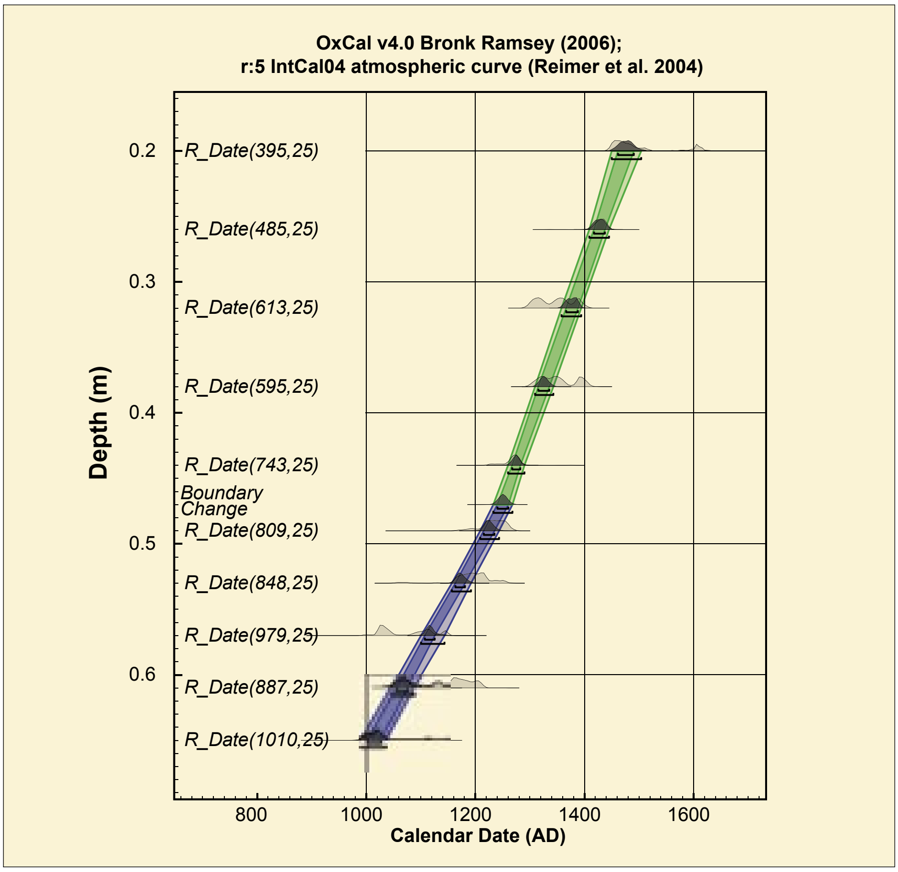

Figure 1: A typical age-depth model from OxCal4 with a series of radiocarbon-dated samples. In this case, the model allows for random fluctuation in deposition rate and for a change in the nature of the sedimentation at a depth of 0.47m. In each sample, a simple calibrated probability distribution function (PDF; light grey), the modeled PDF (dark grey) and the age depth model at the 68% and 95% probability levels (colored bands) are shown. This example is taken from the online manual for the program.

Deposition models in OxCal version 4

OxCal is a computer program for analysis of chronological information. It is freely available for online use or for download to PC or Mac from http://c14.arch.ox.ac.uk/oxcal.html. Although it is most often used for the straightforward calibration of radiocarbon dates, it can also be used to build chronological models of various kinds, using a range of different dating techniques. Previous versions of the program enabled the stratigraphic order of samples to be constrained within a sequence, and also catered for the special case of known age gaps when 'wiggle-matching' radiocarbon-dated tree-ring sequences to the calibration curve.

The new version of the program caters for a much wider range of deposition models. These models were first discussed at the INTIMATE workshop in Iceland in September 2005 (Bronk Ramsey, in press). They range from the loose constraint that dates must be in a particular order (called the Sequence model) to the rigid assumption that the deposition is assumed to be uniform in nature with a constant rate (called the U_Sequence model). Both of these models have been implemented before in several software packages. However, the true situation usually lies between these extremes and a model that allows for random fluctuations in deposition (called the P_Sequence model) is also included and should be appropriate in a much wider range of situations. In many cases, where there are large-scale exposures or multiple cores, the degree of fluctuation in deposition rate can be independently assessed, in other cases this needs to be assessed from the nature of the sediments, or from the dating information itself.

Figure 1 shows one such simple age-depth model and Figure 2 shows the effect of the model on our estimate for the age of one particular sample in the series. The main advantage of using such mod-

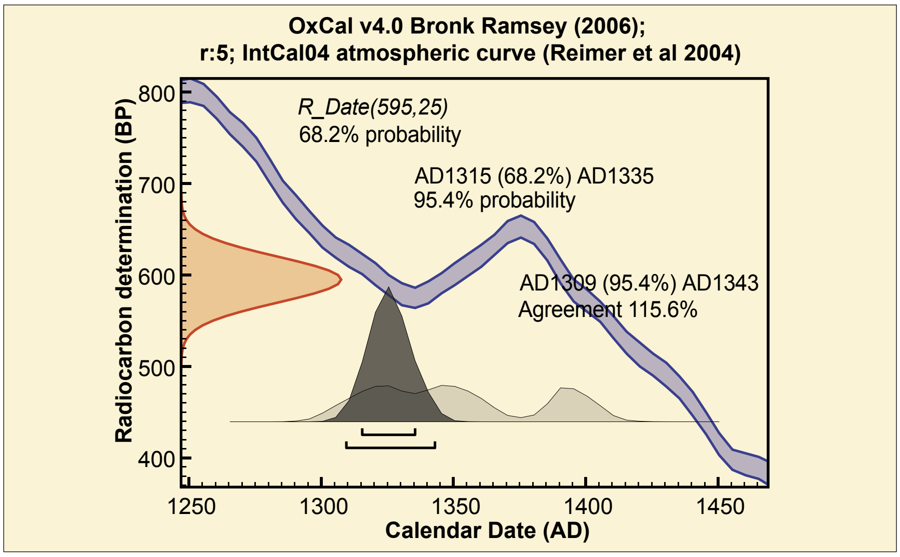

Figure 2: A typical radiocarbon calibration probability distribution (light grey) based on the radiocarbon determination represented by the normal distribution (left axis; red). The result of the overall age model on this particular sample is shown in dark grey. Such resultant probability distributions can be generated for any point in the deposition model (including levels not directly dated).

els is that you get a realistic assessment of the uncertainty of age at any depth. This is important if deciding whether changes or events recorded in a sequence are really synchronous with those in other similarly modeled sequences.

Integrating temporal information into one model

Although generating age-depth models with properly estimated uncertainties is certainly an advance, in many ways the real power of this approach is the ability to integrate information from several different records together. If we have truly synchronous markers, such as tephra, present in the records, then this information can be incorporated into an overall model giving better chronological resolution and, more critically, good relative date information between the records in question—even at some distance from the tie points. In other cases, the tie points might link the chronology to that of the ice cores and allow comparison of climatic information from very different locations.

The other positive aspect of a numerical model of this kind is that it can easily be used to generate other information of interest, for example, the age difference between two events, or the deposition rate for a segment of a particular record. The information obtained in this way is also given in the form of a probability distribution function, with properly assessed uncertainties.

Conclusions and prospects

The questions that need to be addressed in the study of past changes in the Earth require a chronological resolution that pushes our dating techniques to their limit. In this context, we can no longer generate age models by simply drawing straight lines through our data; we need to estimate the uncertainties in our age models and we need to allow for the kinds of natural fluctuations that take place in deposition.

The suite of models now available in OxCal (Bronk Ramsey, 2007), and in other analysis packages such as BPeat (Blaauw and Christen, 2005) allow us to start to address these issues in a comprehensive way. In some cases, such an approach may simply tell us that the information we have is not sufficient to answer some of the key questions. However, in other cases, the ability to integrate information from so many different sources may allow us to see patterns and processes in action that had previously been obscure.

Note

More information on the methods discussed in the article, including links to the program are given on:
http://c14.arch.ox.ac.uk/oxcal.html

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21st century suck-in or smear: Testing the timing of events between archives

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Introduction

Proxy-archives are frequently compared with other data in order to imply teleconnections between regions. Well-known examples of widely recorded past climate events are the last glacial-interglacial transition, the "8.2 kyr event", and the "Little Ice Age". Although we do not question the existence of these events, reported synchronicity between archives could have been caused by age-modeling errors, mistaken interpretations of proxy data, or even by "wishful-thinking". Archives could have been tuned to other archives, age-models selected subjectively, non-responsive sites neglected, or suggestive lines drawn connecting events between archives. It is this potentially dangerous practice of sucking-in or smearing of events (cf. Baillie, 1991; Wunsch, 2006) that we will discuss here. We apply recently developed methods (Blaauw et al., in press) to test the timing of events between two well-dated archives.

Common approaches

Let's start with a short review of the usual steps to date and compare non-annual archives:

1) Single archives are dated by, for example, radiocarbon at several depths.
2) These dated levels, with their often considerable chronological uncertainties, are reduced to point estimates (e.g. the midpoints of the calibrated ranges for ^{14}C dates).
3) A single curve is drawn through these points (e.g. linear interpolation, regres-

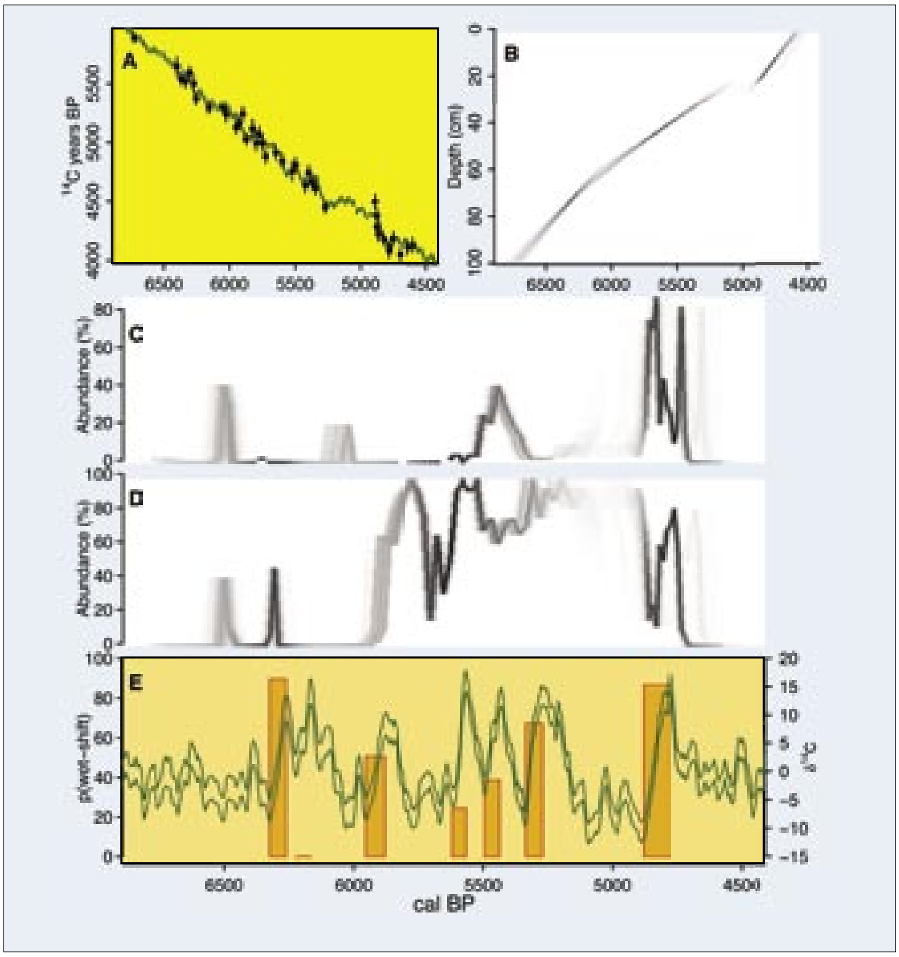

*Figure 1: Age-modeling of core MSB-2K from a raised bog deposit in The Netherlands (Blaauw et al., 2004). **A**: Best fit of the ^{14}C dates to the IntCal04 calibration curve. **B**: millions of age-depth models indicate likely (dark) and more uncertain (light-grey) cal years for every depth of a core. **C**: The age-models from B are plotted, replacing the depths by the values of the proxy Sphagnum cuspidatum at those depths (Blaauw et al., in press). **D**: as C but for proxy Scheuchzeria palustris. **E**: Green lines show 1-σ uncertainty envelope of $\Delta^{14}C$ (measured to yearly precision using dendrochronology; right y-axis). Orange bars are placed during major rises of $\Delta^{14}C$, their heights showing the probability that a wet-shift took place in core MSB-2K during these time-windows (left y-axis).*

sion), which then forms the age-model; this age-model entirely neglects the often considerable chronological uncertainties connected to both the dates and the modeling assumptions.

4) It is this single curve which is then used to convert every depth (either dated or non-dated) to a single calendar age, after which line diagrams are drawn to show the proxy values against calendar age. 5) These proxy diagrams are compared with other studies, in graphical comparisons where it is up to the reader to "eyeball" synchronous events (although authors often help their readers by connecting peaks between archives with lines; see also Wunsch, 2006).

Age-model uncertainties

We argue that the above process can easily lead to overly subjective comparisons, and that more systematic tests for synchronicity between archives are needed (Blaauw et al., in press). Firstly, we propose to step away from using just one curve to translate depths into calendar ages. Using Bayesian methods, it is possible to construct millions of likely age-models, including information such as that dates in a sequence are ordered chronologically, and that some accumulation rates are more likely than others (Blaauw and Christen, 2005). Each of these age-models will give a slightly different calendar age estimate to the depths of a sequence. For every depth, the likely calendar ages can be plotted as grey-scales, with darker colors indicating more likely calendar ages (Fig. 1). The same age-models can be used to plot proxy values against calendar age, again indicating more likely calendar ages by darker values and thereby visualizing the chronological uncertainty of proxy values (Blaauw et al., in press; Fig. 1). Dark areas indicate secure chronologies, while light grey areas warn us of insecure areas (e.g. around 5000 cal BP in Fig. 1, at the time of a likely hiatus in the shown sequence).

Testing for events

Now let's take a closer look at Figure 1. The core was sampled from a Dutch raised bog deposit and dated at high resolution (40 ^{14}C dates over the 1-m-long core; Blaauw et al., 2004). The grey-scale graphs in panels C and D show the chronologies (including uncertainties as explained above) of two wetness-indicating bog plant species; rising values are interpreted as changes towards wetter conditions. Using the eye-balling approach, it is interesting to note that many wet-shifts apparently correspond with sharp rises in $\Delta^{14}C$ (indicating decreases in solar activity; panel E), for example around 6300, 5900, 5500, 5300 and 4800 cal BP. However, using the previously mentioned millions of likely age-models, we can calculate the actual probability that these wet-shifts occurred during periods of rising $\Delta^{14}C$ levels. We do this by choosing a time-window, for example 4880-4775 cal BP that corresponds to a large rise in $\Delta^{14}C$, and then calculating which proportion of the millions of age-models assigns an age within this time window to those depths where wet-shifts were found (Blaauw et al., in press). The heights of the orange bars in the lowest panel of Figure 1 show the probabilities that wet-shifts took place during rising $\Delta^{14}C$ levels. Some of these probabilities are reassuringly high (close to 100%) but others linger around 20-40%, which clearly is less convincing.

Conclusion

We think that incorporating chronological uncertainties in analysis of proxy data forms one step towards more systematic and less subjective use of proxy data. Here, the above methods have been applied to ^{14}C-dated peat deposits, but the approach could be adapted to many other types of Quaternary environmental change archives. Hopefully, the age-depth modeling research outlined above will eventually enable us to find out which types of questions can, and which cannot, be confidently answered using proxy data. This is currently one of the biggest obstacles in Quaternary environmental change research.

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High-resolution radiocarbon chronologies and synchronization of records

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^{14}C wiggles — age plateaus and jumps

It is now accepted that the precise dating of certain periods is complicated by extreme variability of atmospheric ^{14}C content shown at times in the 14C calibration curve. This complication arises from variations in atmospheric ^{14}C content and is known as wiggles in the calibration curve. Radiocarbon age 'plateaus', are caused by a decrease in the atmospheric ^{14}C concentration and appear as a slowing down of the 14C clock such as occurred during the Younger Dryas (YD) chronozone. In effect, similar ^{14}C ages apply across a range of up to 500 calendar years. The opposite is observed when atmospheric ^{14}C levels increase so that the ^{14}C clock appears to speed up. In such cases, which include the beginning of the YD and Pre-Boreal intervals, the true age of a sample, taking dating errors into account, may spread across a comparatively wide ^{14}C age range.

The fluctuations of atmospheric ^{14}C content ($\Delta^{14}C$) are driven by changes in the ^{14}C production rate due to variations in the geomagnetic field and solar activity, and by changes in the carbon cycle related to climate change (Hughen et al., this issue). However, the intricate connection between variable atmospheric ^{14}C content and climate change still remains to be resolved (Goslar et al., 1999). Whatever the underlying reasons for the $\Delta^{14}C$ fluctuations, they are not only a source of complication but also offer means of resolution. Specifically, the application of wiggle-matching and Bayesian statistical techniques provide a basis for high precision ^{14}C chronologies for key proxy records from terrestrial and marine sites around the globe. These improved chronologies may, in turn, provide new clues to better resolve the causes for $\Delta^{14}C$ fluctuations (as well as to better understand the functioning of the climate system as a whole).

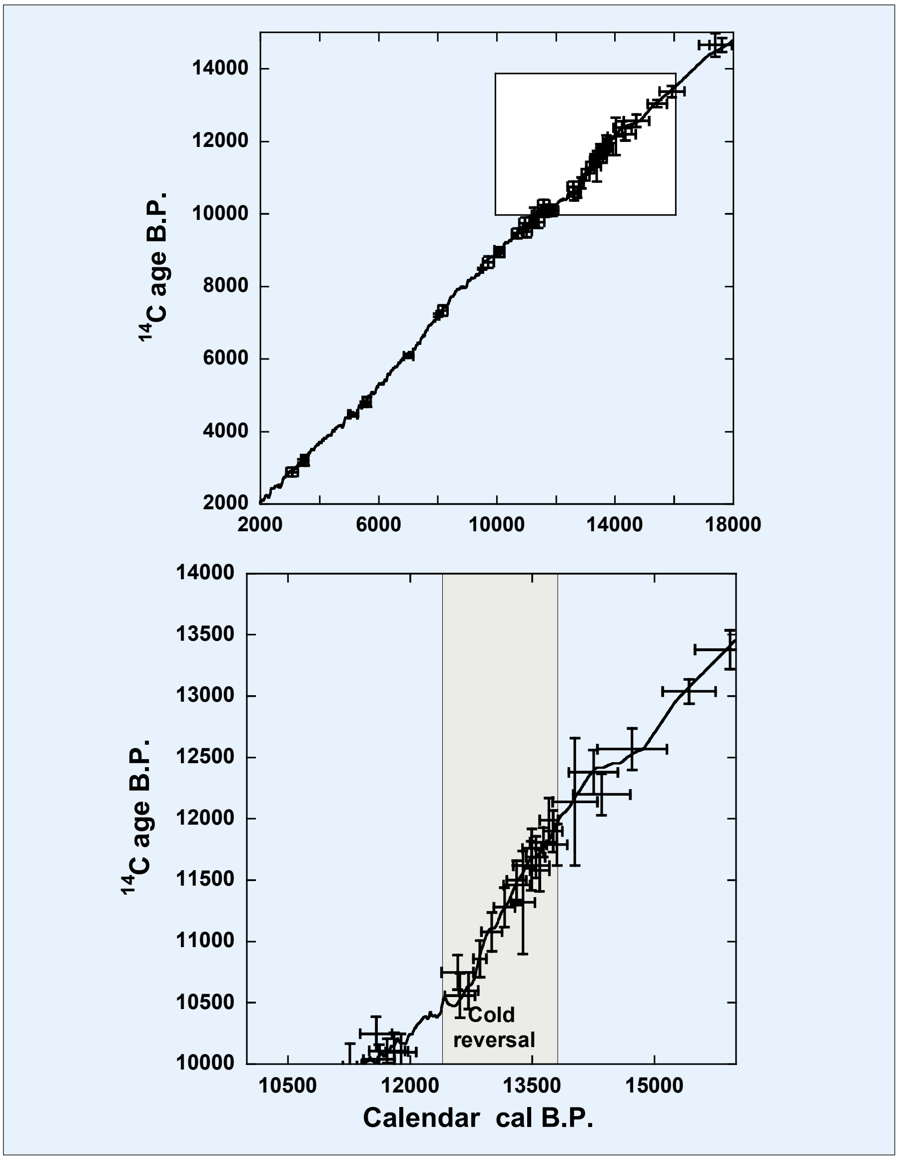

Figure 1: Combined age data set (including all independent tephrochronological ages) from Kaipo Bog late-glacial sequence wiggle-match fitted using OxCal v3.10 to the calibration curve INTCAL04. Lower panel shows a close-up of the pre-Holocene interval. The cold reversal period, defined by palynology, is marked.

High-resolution ^{14}C timescales

An increasing trend towards high-resolution climate records, in particular from polar ice cores has generated demand for comparable high-resolution ^{14}C dating and comparison with other paleo-records of the last 40-50 kyr from terrestrial and marine archives. Although the presence of ^{14}C plateaus and wiggles is seen as problematic in this regard, recent dating of key sequences from peat bogs and lakes has shown ways of bypassing the problem (Hajdas et al., 1993, Hajdas et al., 1995, Kilian et al., 2000). Hajdas et al. (2004) used a wiggle-matching method to fit sequences of ^{14}C data to the calibration curve and thereby provide a means of more precise calibration. Other applications have used wiggle matching to the calibration curve to develop a floating chronology for terrestrial varve sequences (e.g., Hajdas et al., 1993, 1995). This method has also been applied to marine records used to extend the calibration curve (Hughen et al., 1998). The Bayesian approach to 14C calibration uses the stratigraphic order of samples to constrain the calibrated age ranges (Ramsey this issue, Ramsey 2001). Associated improvements in chronostratigraphic precision raise the confidence with which the timing of events or features of interests can be compared between spatially disparate records, as briefly illustrated below.

Northern hemisphere records

A striking example is the dating of cold events that occurred at the close of the last deglaciation around 12-10 kyr BP (14 to 12.5 kyr cal BP). Until recently, reliable dating of this interval was hampered by the lack of a dendrochronological calibration curve, and by the age plateau and rapid jumps that characterize the YD (see above). Extension of the calibration curve and the new data sets of INTCAL98 and INTCAL04 (Stuiver and Reimer 1998, Reimer et al., 2004) have enabled reconstruction of the fluctuations in atmospheric ^{14}C content during the YD, and provided the basis for wiggle-matching ^{14}C chronologies. The characteristic ^{14}C changes have themselves become time markers. For example, the chronology established for the Kråkenes Lake sequence (Norway) was the first to show the coincidence between a dramatic change in ^{14}C ages (11-10.6 kyr BP) and the onset of cooling at the beginning of the YD (Gulliksen et al., 1998). This coincidence has subsequently been observed in other records from European lakes, such as: Soppensee (Switzerland), Holzmaar (Germany), (Hajdas et al., 1993, 1995), Madtjärn (Sweden) and Gościąż (Poland) (Goslar et al., 1999). High-resolution ^{14}C dating of a deglacial cold event found on Kodiak Island also showed that Alaska experienced cooling which was synchronous with the YD in the North Atlantic region (Hajdas et. al. 1998).

Southern Hemisphere Records

The radiocarbon dating of the New Zealand Franz-Joseph Glacier re-advance at ca. 11 kyr BP (Denton and Hendy 1994) sparked debate on the global extent of YD cooling and drew attention to records from the Southern Hemisphere. A high-resolution ^{14}C chronology for the Kaipo Bog sequence from New Zealand provides further insight into a cold reversal that preceded early Holocene warming (Hajdas et al., 2006). In total,, 51 age points for Kaipo Bog were fitted to the INTCAL04 calibration curve (Reimer et al., 2004) via the OxCal (version 3.10) sequence calibration (Ramsey, 2001) (Fig. 1), which uses a Bayesian approach that incorporates known parameters into the fitting procedure. In this case, the known stratigraphy—age superposition with depth—defined the fitting procedure. This procedure resulted in reduced errors for calibrated ages and gave a continuous sequence of calendar ages independent of ^{14}C age plateaus or wiggles. Based on this chronology, cooling at Kaipo commenced between 13,820 and 13,590 cal yr BP (12,030 ± 90 ^{14}C yr BP) and ended ~1000 years later between 12,800 and 12,390 cal yr BP (10,790 ± 70 and 10,600 ± 90 ^{14}C yr BP). This improved chronology reveals that the cold event was not synchronous with the YD, an alternative scenario possible with the original chronology (Newnham & Lowe, 2000). High-resolution radiocarbon chronologies from two Patagonian sites, Huelmo (Chile) and Mascardi (Argentina) (Hajdas et. al. 2003) have also shown that the cold events observed in those two records preceded the YD chronozone by some 500 years but terminated close to the end of the YD.

In summary, these examples illustrate the potential of high-resolution radiocarbon dating for development of reliable timescales of Holocene and late-glacial records around the globe. Extension further back in time and refinement of the calibration curve will facilitate application of similar approaches to older time periods.

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For full references please consult:
www.pages-igbp.org/products/newsletters/ref2006_3.html

Marine ^{14}C reservoir ages oscillate

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The current ^{14}C calibration scale, IntCal04, is tree-ring based up until 12.4 cal kyr BP but relies for the older part, up to 26 cal kyr BP, on surface-ocean data from planktic foraminifera and corals at a number of carefully selected locations (Reimer et al., 2004). In order to do so, it is assumed that a constant global marine reservoir age of 405 ± 22 yr, obtained by box modeling the period AD 1350-1850, and a constant local deviation from this global value, ΔR, can be applied beyond the range of tree-ring calibration. The (local) marine reservoir age under equilibrium conditions is determined by the balance between restricted ocean-atmosphere gas exchange and limited mixing between the mixed layer and the deep ocean. For the selected locations, reservoir ages close to 400 yr indicate that this limited exchange results in a ~5% ^{14}C deficit in the ocean mixed layer. The assumption that this reservoir age has remained constant in the past implies that (i) this mixing balance has been maintained, (ii) the general ocean circulation "pipeline" system, that is the system of thermohaline currents has not changed, and (iii) equilibrium has not been disturbed by changes in the production rate of cosmogenic isotopes, or (iv) in the size of the atmospheric carbon reservoir.

Dramatic climate changes occurred during the early stages of the last glacial to interglacial transition 19-14.5 kyr. They were accompanied by the most fundamental recent changes in ocean circulation, which also likely contributed to major shifts in CO_2 transfer from ocean to atmosphere, leading to the well-known deglacial rise in atmospheric pCO_2 from 190 to 240 ppmv at 14.5 kyr (Monnin et al., 2001; Köhler et al., 2005). For the preceding glacial period, back to the limit of radiocarbon dating around 50 kyr, ice core records provide further evidence for frequent large and rapid changes in climate and low atmospheric CO_2 concentrations in the range of 190 to 230 ppmv. Marine records now have confirmed these findings and shown that these events were in many cases coeval with large changes in the meridional overturning circulation of the oceans. During this period, global sea level also dropped, with stadial-interstadial related fluctuations, to a low of more than 120 m below present sea level at the last glacial maximum (23-19 kyr), before rising over the deglacial and early Holocene to present levels. Reconstructions of the paleointensity of the Earth's magnetic field from various ocean sediments (GLOPIS 75; Laj et al., 2004) give evidence of several episodes with a very weak earth magnetic field leading to increased production of cosmogenic isotopes, especially around 41 kyr BP; the Laschamp Event (Hughen et al., 2004a; Voelker et al., 2000). Thus, it seems that most of the conditions for constant marine reservoir ages—constant basin geometry, ocean circulation, ocean–atmosphere and surface–deep ocean mixing, ^{14}C production, and atmospheric reservoir size—have been violated. Although careful application of U/Th dating, supplemented by volcanic time markers—identified and dated in ice cores and/or terrestrial records—may supply absolute ages for the marine data set, the atmospheric ^{14}C content cannot be reconstructed as long as the local marine reservoir age at each particular point in time is not known.

Therefore, a secure correlation between single events in the ocean and on

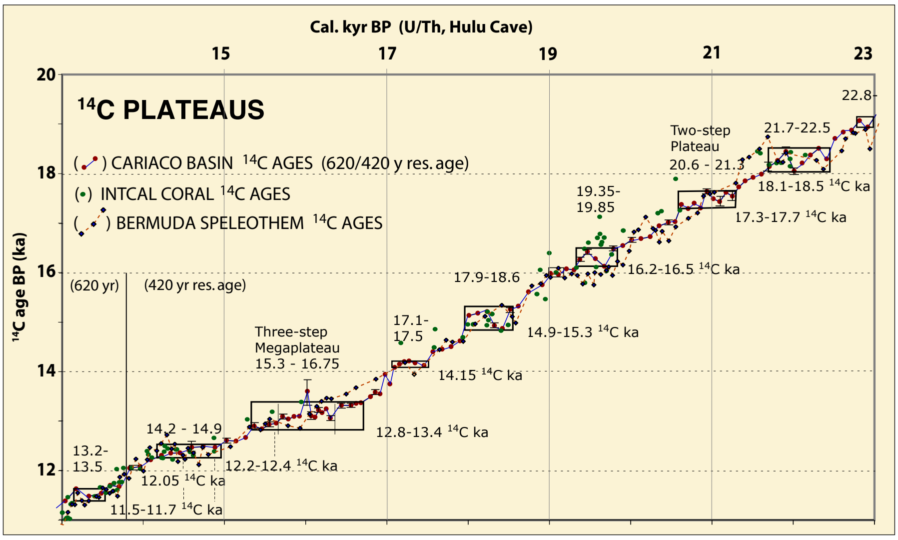

Figure 1: ^{14}C plateaus and their assigned boundary ages compiled by Sarnthein et al. (in press) from (1) the ^{14}C record of Cariaco Basin ODP Site 1002 for Termination Ia (Hughen et al., in press), (2) the combined set of Marine04 coral ages (Fairbanks et al., 2005; Reimer et al., 2004) (green dots), and (3) the Bermuda speleothem record (Beck et al., 2001, suppl.) (blue dots and dashed orange line). 1-σ bars are given for ^{14}C ages, where analytical error exceeds red-dot diameter. ^{14}C ages of <13.8 kyr are corrected for additional 200-yr reservoir effect (Kromer et al., 2004 and by comparison with Marine04 coral ages).

land based on ^{14}C dating cannot yet be established.

At near-shore sites, local reservoir ages are generally derived from paired dates of terrestrial material and marine shells. Reliable sample pairs are, however, hard to find and provide only one point in time. A new possibility to study varying reservoir ages is offered by apparent "plateaus" in the ^{14}C age depth relationship that turn up in densely dated, high-resolution sediment records, just as they do in the age-calibrated atmospheric ^{14}C record. This is to be expected and, under the ideal situation of constant marine reservoir, the ^{14}C age plateau of planktic foraminifera in the sediment should even be identical to that in the atmosphere. Yet, even under less than ideal conditions, atmospheric ^{14}C plateaus may still be recognized in sediment sections with high-resolution dating (spacing <200-400 yr) and, because the atmosphere is globally well mixed, provide a means of event correlation.

In a first application to an interval prior to tree-ring calibration, Sarnthein et al (in press) identified a reference suite of seven ^{14}C "plateaus" (i.e. intervals with low or reversed ^{14}C change vs calendar age) of variable length in the age-calibrated Cariaco ^{14}C record (Hughen et al., in press), and used this sequence for event correlation with four cores from key locations of the oceanic thermohaline circulation in the Pacific and Atlantic.

The suite of plateaus extends over the Last Glacial Maximum (LGM) and Termination-Ia intervals between 23 and 14 cal kyr in the partly varved marine sediment record at ODP Site 1002, Cariaco Basin (Hughen et al., in press; 2004a). The plateau-style structures defined in the Cariaco ^{14}C record largely match a number of coeval features in the 230Th-dated Bahama stalagmite record of atmospheric ^{14}C concentrations over the same deglacial interval (Beck et al., 2001) (Fig. 1), most conspicuously in the oldest (>21.7 cal kyr) and younger sections of the record (at <18 cal kyr), despite potential variations in reservoir age in Cariaco and dead carbon contribution in the speleothems. The cumulative IntCal04 set of coral-based paired 230Th and ^{14}C ages (Fairbanks et al., 2005; Hughen et al., 2004b) also confirms most plateau structures and their ages, e.g. at 23.0-21.5, 19.0-17.5, and in particular between 16 and 13 cal kyr. The Cariaco record, with its high-resolution timescale derived by correlation to the 230Th-dated timescale of the Hulu Cave stalagmite (Wang et al., 2001), provides the best available chronological standard sequence. Fluctuations in its reservoir age, assumed to be a constant 420-yr, will result in reservoir ages derived for other records that are off by the same amount, which makes their later correction easy.

Past ^{14}C marine reservoir ages of surface and bottom waters between 23 and 14 cal kyr were determined at one Atlantic (Iceland Sea) and three Pacific (South China Sea, Northwest Pacific, Santa Barbara Basin) locations. Sarnthein et al. (in press) identified a series of planktic ^{14}C plateaus in each record and tuned these to the Cariaco-based sequence of shorter and longer "atmospheric" reference plateaus. The calendar ages determined for the beginning and end of each of the seven reference ^{14}C plateaus provide the first accurate calendar age estimates for global deglacial marine records with an uncertainty determined by that of the correlation and the Cariaco age uncertainties (from ~270 yr beyond 20 kyr, and ~500 yr for 20-18.5 kyr, to 130-200 yr for 18.5-14.0 kyr; Hughen et al., in press). The ^{14}C age differences between the tuned and the reference plateaus represent the paleoreservoir ages of local surface water. Benthic apparent ventilation ages are the difference between coeval planktic and benthic ^{14}C ages plus the planktic reservoir age. Opposite trends in the reservoir ages obtained indicate major changes in deglacial meridional overturning circulation (MOC) during and after the late phase of Heinrich 1 (H1) stadial. In the subarctic northwest Pacific, these reservoir ages decreased in deep waters from 2800 to 1150 yr, in surface waters to 300 yr (vs >850 yr today), and in North Pacific upper intermediate waters from 4400/3800 to 2000 yr. By contrast, in the Icelandic Sea, source region of modern MOC, intermediate-water reservoir ages increased during LGM and H1 from 440 to >2000 yr, reflecting a brief northward reversal of Denmark Strait Overflow waters. The two best-established major atmospheric ^{14}C plateaus during late H1 and the early Bølling interstadial match the coeval two-step deglacial rise in atmospheric pCO_2 and appear to reflect major ocean CO_2 exhalation that resulted from MOC change and deep-ocean flushing.

The surprisingly large and diverse changes in reservoir ages obtained from the ^{14}C plateau tuning, and their apparent correlation with major changes both in oceanic circulation and in the carbon cycle, illustrate that deriving an atmospheric ^{14}C calibration from marine data and calibrating marine ^{14}C ages is not simple. On the other hand, the use of a suite of ^{14}C age plateaus in marine records for event tuning appears to offer the possibility both for global, reservoir-independent correlation between marine and terrestrial records and for the determination of local reservoir ages and oceanic mixing.

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Are insolation and sunspot activity the primary drivers of Holocene glacier fluctuations?

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Recent research has documented significant, rapid fluctuations of climate throughout the Holocene (Masson et al., 2000; Bond et al., 2001; Mayewski et al., 2004; Jackson et al., 2005; Willard et al., 2005). One of the sources of proxy paleoenvironmental information that has long been used to document Holocene climate variability is alpine glacier fluctuations (e.g., Denton and Karlén, 1973). Most alpine glaciers react rapidly to changes in their mass balance and thus to changes in temperature and precipitation, and studies of past glacier fluctuations allow reconstruction of climate variability on centennial and decadal timescales.

We have compiled evidence for Holocene glacier fluctuations in western Canada and compared this data set with global data on Holocene glacier fluctuations. Our objective is to evaluate the hypothesis that Holocene alpine glacier fluctuations are driven by changes in solar irradiance.

Global Holocene glacier fluctuations

A complete reconstruction of Holocene glacier fluctuations is difficult because glacier advances in the Northern Hemisphere during the past millennium were the most extensive of the Holocene and, consequently, obliterated or obscured most of the evidence of previous advances. Furthermore, older moraines, where present, are commonly poorly dated. Perhaps the best evidence for glacier advances prior to the last millennium is found in glacier forefields deglaciated in the twentieth century. Remnants of forests in these forefields include in situ tree stumps and detrital logs and branches. Organic soils and detrital wood are also exposed in some composite lateral moraines exposed by recent glacier retreat. High-quality data on Holocene glacier fluctuations have been retrieved from many of these forefields and moraines (Luckman, 2000; Nicolussi and Patzelt 2000; Calkin et al., 2001; Osborn et al., 2001, in press; Wiles et al., 2002; Glasser et al., 2004; Koch et al., 2004, in press; Reyes and Clague, 2004; Holzhauser et al., 2005).

We have compiled published data on Holocene glacier fluctuations in western Canada and compared them to data from other temperate mountainous areas including the Patagonian Andes, European Alps, Alaska, Scandinavia, and New Zealand. The Canadian data set comprises 256 radiocarbon-dated samples, mainly from the southern and central Canadian Rocky and Coast Mountains (Luckman, 1977, 1995, 1996, 2000; Luckman et al., 1993; Smith and Desloges, 2000; Osborn et al., 2001, in press; Larocque and Smith, 2003; Koch et al., 2004, in press; Lewis and Smith, 2004; Reyes and Clague, 2004).

The most recent regional and global compilations of Holocene glacier fluctuations date to the 1970s and 1980s (Denton and Porter, 1970; Denton and Karlén, 1973; Porter, 1986; Röthlisberger, 1986; Calkin, 1988; Clapperton and Sugden, 1988; Davis, 1988; Gellatley et al. 1988; Karlén, 1988). We have augmented these data sets with new data from Alaska (Calkin et al., 2001; Wiles et al., 2002), the U.S. Pacific Northwest (Harper, 1993), the European Alps (Nicolussi and Patzelt, 2000; Hormes et al., 2001; Holzhauser et al., 2005; Joerin et al., 2006), Patagonian Andes (Wenzes, 1999; Glasser et al. 2004; Douglass et al., 2005; Koch and Kilian, 2005), Scandinavia (Winkler, 2003; Winkler et al., 2003; Shakesby et al., 2004; Bakke et al., 2005), and New Zealand (Winkler 2004). Chronological control for these studies was provided by dendrochronology, lichenometry, radiocarbon dating of fossil wood in moraines, cosmogenic surface exposure dating, proglacial lake sediments, and tephras. The augmented data sets allow us to compare Holocene glacial fluctuations in western Canada with those in other regions with greater clarity than has been possible in the past.

These records provide evidence for broadly synchronous periods of glacier advance around the world at 8600-8100, 7300-5900, 5100-4200, 4200-1900, 1900-900 cal yr BP, and during the past millennium (Little Ice Age) (Fig. 1). The broad age ranges of the six periods of more extensive glaciation are the result of large uncertainties introduced by calibrating radiocarbon ages. Glacier extent at the end of each of the six periods, however, was much greater than at the beginning of the following advance period. Synchronicity between regions and hemispheres indicates that climate is being forced by a single mechanism or a combination of mechanisms that is global in its effect.

Forcing of global Holocene glacier fluctuations

The global data set discussed above was used to evaluate the hypothesis of Denton and Karlén (1973) and Karlén and Kuylenstierna (1996) that Holocene alpine

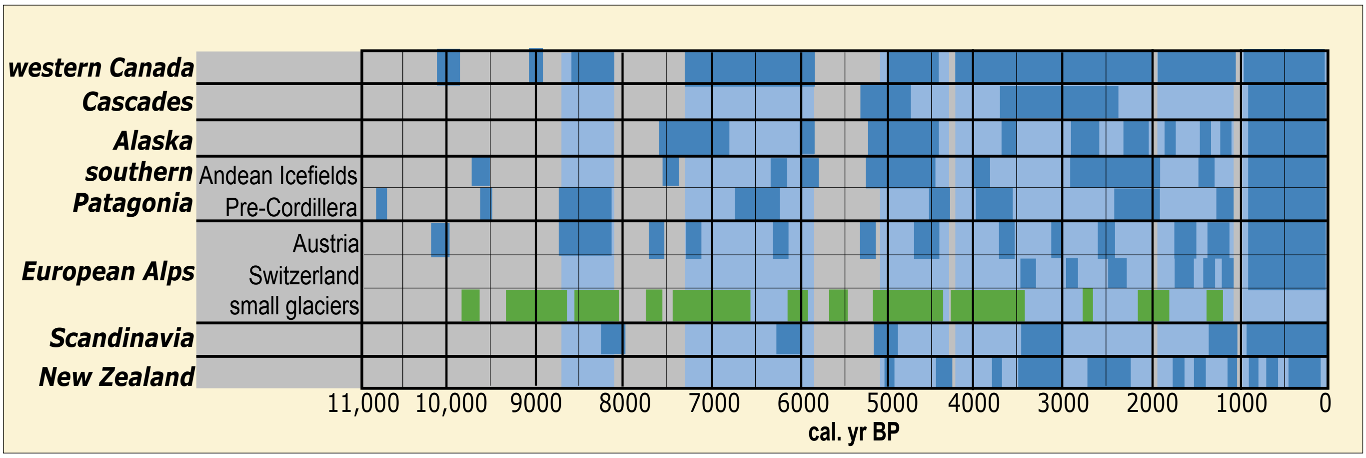

Figure 1: Timing of global glacier fluctuations during the Holocene. Horizontal blue bars indicate times of glacier advance; horizontal green bars are times when glaciers in the Swiss Alps were relatively small; vertical light blue bars are periods of glacier advance based on the global data set.

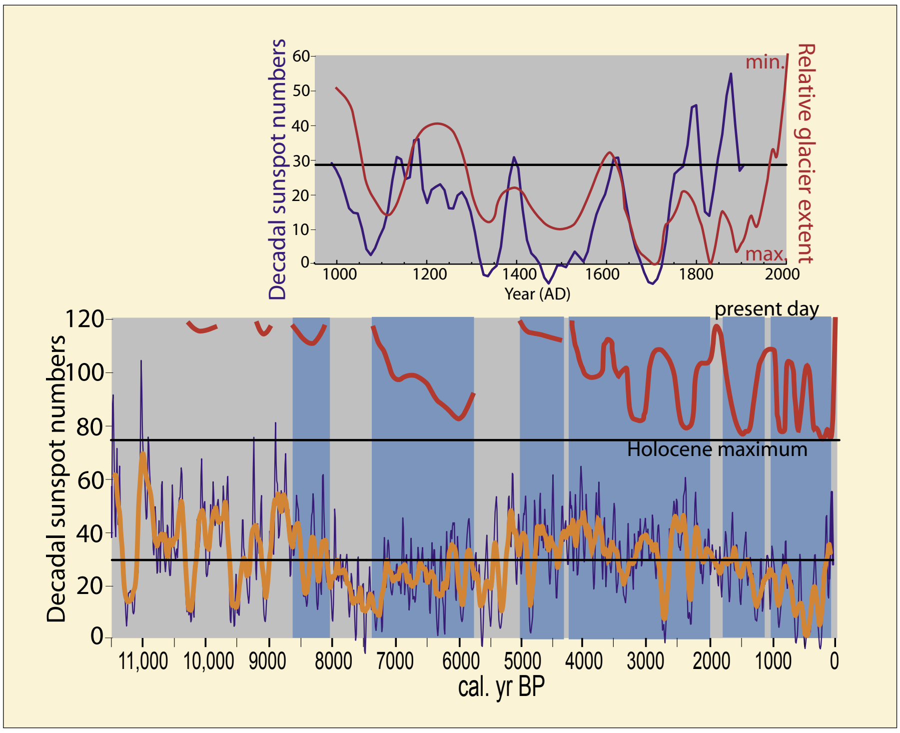

Figure 2: Glacier fluctuations in western Canada and reconstructed decadal sunspot numbers (Solanki et al., 2004) during the Holocene (bottom) and the past millennium (top). The red line represents relative glacier extent through time (top is present extent; bottom is maximum Holocene extent). The blue line shows decadal sunspot numbers, and the orange line (bottom) is an 11-point smoothed reconstruction of sunspot numbers. The blue vertical bars (bottom) indicate periods of global glacier advance. The negative reconstructed sunspot values are an artefact introduced by uncertainties in the reconstruction (Solanki et al., 2004).

glacier fluctuations were caused by variations in solar irradiance. Our evaluation is based on the most recent reconstruction of Holocene sunspot activity by Solanki et al. (2004). They inferred variations in solar irradiance on a decadal timescale to AD 1950 from changes in the production of atmospheric ^{14}C stored in trees.

Our analysis indicates that, on a centennial timescale, major Holocene glacier advances coincide with times of low sunspot activity (Fig. 2). It also confirms previous suggestions (Lawrence, 1950; Wiles et al., 2004; Luckman and Wilson, 2005) that sunspot activity and glacier fluctuations coincide on a decadal timescale during the past millennium (Fig. 2).

The relative extents of synchronous glacier advances in the two hemispheres, however, are different (Fig. 3). Glaciers in the Northern Hemisphere were most extensive in the late Holocene, whereas those in the Southern Hemisphere were most extensive in the early Holocene. These differences are probably due to changes in solar insolation in the two hemispheres over the course of the Holocene. During the early Holocene, insolation was high in the Northern Hemisphere and low in the Southern Hemisphere, consistent with the greater extent of glaciers in the south than in the north. In contrast, in the late Holocene, insolation was low in the Northern Hemisphere and high in the Southern Hemisphere, again consistent with the greater extent of glaciers in the north than in the south.

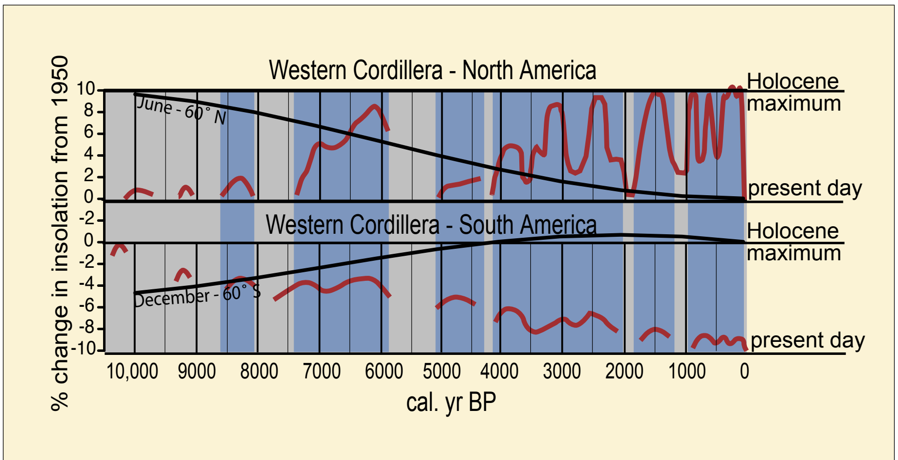

Figure 3: Patterns of Holocene glacier fluctuations in the Cordilleras of North and South America, which are considered representative of the two hemispheres, and summer insolation at 60°N and S after Bradley et al. (2002). The vertical blue bars indicate periods of global glacier advance.

Conclusions

Recently published data on Holocene glacier fluctuations show that glacier advances on different continents and the two hemispheres were broadly synchronous, with major advances at 8600-8100, 7300-5900, 5100-4200, 4200-1900, 1900-900 cal. years BP, and during the past millennium. Synchronicity implies that one or more mechanisms have operated on a global scale to force climate change during the Holocene. Major glacier advances occur at times of low sunspot numbers on centennial and decadal timescales. Global glacier recession in the twentieth century may be partly due to high sunspot numbers, but changes in solar irradiance cannot be the sole cause of observed warming and glacier recession during the past three decades (Solanki et al., 2004). The differences in glacier extent between the Northern and Southern Hemispheres during successive Holocene advances are attributed to differences in solar insolation between the two hemispheres. Glacier advances were less extensive when solar insolation was high, that is in the early Holocene in the Northern Hemisphere, and in the late Holocene in the Southern Hemisphere.

Acknowledgements

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Holocene trends in tropical Pacific sea surface temperatures and the El Niño-Southern Oscillation

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Introduction

The El Niño-Southern Oscillation (ENSO) dominates modern climate variability and considerable effort has been invested in reconstructing its history. Much of this effort has focused on the Holocene for two important reasons: (1) Holocene boundary conditions have been similar to present-day (the orbital configuration being an important exception) providing a useful analog for long-term ENSO dynamics in an interglacial climate; and (2) a growing number of studies indicate significant Holocene ENSO changes, including a marked decline in activity in the early-middle Holocene (e.g. Moy et al., 2002). If correct, the latter implies that strong ENSO reorganizations can arise from gradual shifts in background climate conditions, which has important implications for the future. However, a number of challenges continue to hinder adequate understanding of the Holocene evolution of ENSO, including: (1) lack of optimally located continuous ENSO archives with annual or sub-annual resolution; (2) lack of a rigorous theoretical underpinning of how ENSO depends on the background (i.e. time-averaged) climate state; and (3) slow progress toward realistic modeling of tropical ocean-atmosphere dynamics, particularly as it applies to the equatorial annual cycle. As a consequence, our understanding of Holocene ENSO variability lags behind that of other tropical climate systems such as the monsoons and the Intertropical Convergence Zone (ITCZ).

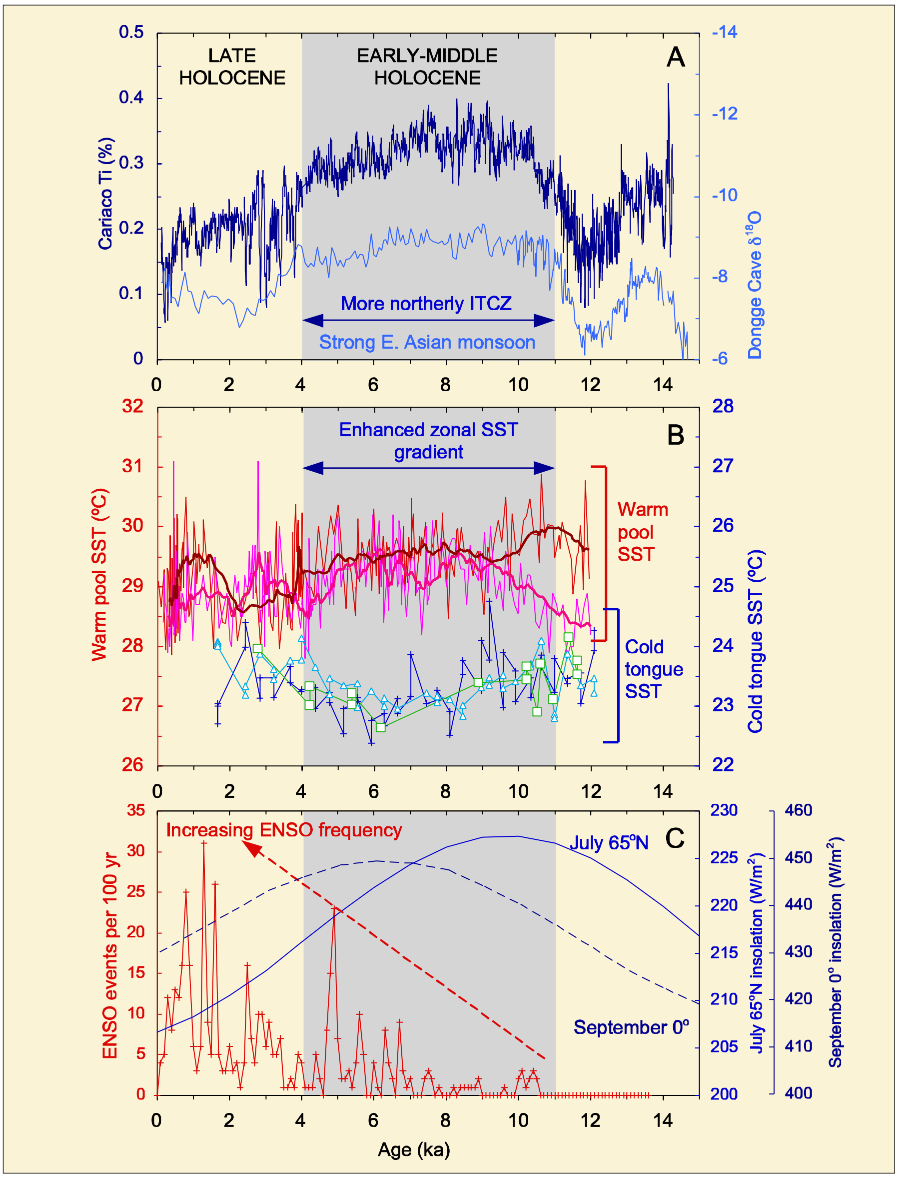

*Figure 1: Holocene climate trends in regions dominated by monsoon, ITCZ and ENSO dynamics: (**A**) Titanium concentrations (%) in ODP site 1002C from the Cariaco Basin (dark blue) (Haug et al., 2001); $\delta^{18}O$ of the D4 stalagmite from Dongge Cave, China (light blue) (Yuan et al., 2004). (**B**) Mg/Ca SSTs from the western Pacific warm pool (MD98-2181, red; MD98-2176, pink) (Stott et al., 2004) and eastern Pacific cold tongue (V21-30, blue; V19-28, green) (Koutavas et al., 2006). (**C**) Holocene ENSO frequency from Laguna Pallcacocha sediment color changes (Moy et al., 2002).*

The role of orbital variations

Monsoon- and ITCZ-related climate anomalies are currently understood as responses to varying northern summer insolation. The July maximum ~10 ky ago is widely thought to have strengthened monsoon activity and accentuated the northerly bias of the ITCZ. It is worth noting that late summer (e.g. September) insolation peaked as late as 6 ky ago (Fig. 1) and in many locations this may have pushed the timing of the climate response well into the mid-Holocene. Accordingly, sites affected by the monsoons typically reflect positive precipitation anomalies spanning much of the early and middle Holocene. Notable examples include speleothems from southeast China (Yuan et al., 2004) (Fig. 1A) and Oman (Fleitmann et al., 2003), and marine records from the Bay of Bengal (Kudrass et al., 2001), the Arabian Sea (Gupta et al., 2003) and the west coast of North Africa (deMenocal et al., 2000). Similarly, locations sensitive to the migration of the ITCZ, such as the Cariaco Basin in the western Atlantic, show evidence for a more northerly mean ITCZ position (Haug et al., 2001) (Fig. 1A).

The potential of orbital forcing to affect ENSO has been demonstrated in climate models (Clement et al., 1999) and is believed to act through its influence on the large annual cycle of sea surface temperature (SST), convection and cloud cover in the eastern tropical Pacific. The interaction between ENSO and the annual cycle has long been regarded as a key element of the low-frequency ENSO modulation (e.g. Tziperman et al., 1994; Chang et al., 1995), giving rise to well-founded expectation that orbital effects, either local or remote, exert a major influence. Unfortunately, realistic simulation of the equatorial annual cycle remains a challenge for current-generation climate models and this limits their usefulness for elucidating the ENSO response to orbital variations. This limitation renders more acute the need for extensive paleo-ENSO reconstructions as a means of advancing our understanding.

Tropical Pacific SSTs

We constrained long-term Holocene SST progression in the tropical Pacific using Mg/Ca thermometry in two sites from the eastern Pacific and comparing the results with records from the west. Cores V21-30 and V19-28 from the equatorial cold tongue revealed consistent SST histories, marked by a broad minimum between 5-9 ky BP (Fig. 1B) (Koutavas et al., 2006). This contrasts with reconstructions from the western Pacific indicating the opposite; warmest conditions prevailed prior to 5 ky BP (Stott et al., 2004). Due to the inverse east-west climate trends, the zonal SST gradient along the equator was 20-30% higher in the early-middle Holocene, a pattern reminiscent of the cold ENSO phase, i.e. La Niña.

It is noteworthy that this anomalous SST configuration coincided with the hemispheric-scale strengthening of the northern monsoons and northward–displaced ITCZ (Fig. 1A). This suggests a common (orbital) origin of the combined monsoon-ITCZ-Pacific SST evolution. But it also hints that coupled interactions among these systems were equally important in accomplishing the observed anomalies. A good example involves the interaction of the ITCZ with equatorial SST and by extension with ENSO. A northward-displaced ITCZ favors strong cross-equatorial winds, which induce upwelling, cool the SST and help maintain the ITCZ displaced north. Given this, one scenario for the anomalous early-middle Holocene climate may involve an initial northerly "nudge" of the ITCZ in response to insolation, which in turn triggers an equatorial ocean response (i.e. cool upwelling) that acts as a positive feedback. An alternative scenario may be that the surface ocean feels the orbital influence first, responding with an amplified Bjerknes feedback, as predicted by the ocean dynamical thermostat of Clement et al. (1996). The resulting cooling in the eastern Pacific serves to keep the ITCZ off the equator.

Holocene ENSO

How does the Holocene history of ENSO fit with these general climate trends? Despite gaps in observations, converging evidence points to weaker El Niño activity in the early-middle Holocene. However, important questions persist:

(a) Was the decline in El Niño accompanied by a de- or increase in La Niña activity?

(b) Was the difference in mean climate conditions a cause or consequence of the altered ENSO?

(c) Was the ENSO dampening associated with a weaker or stronger seasonal cycle?

(d) Was the change triggered by local (equatorial) or remote (extratropical) orbital mechanisms?

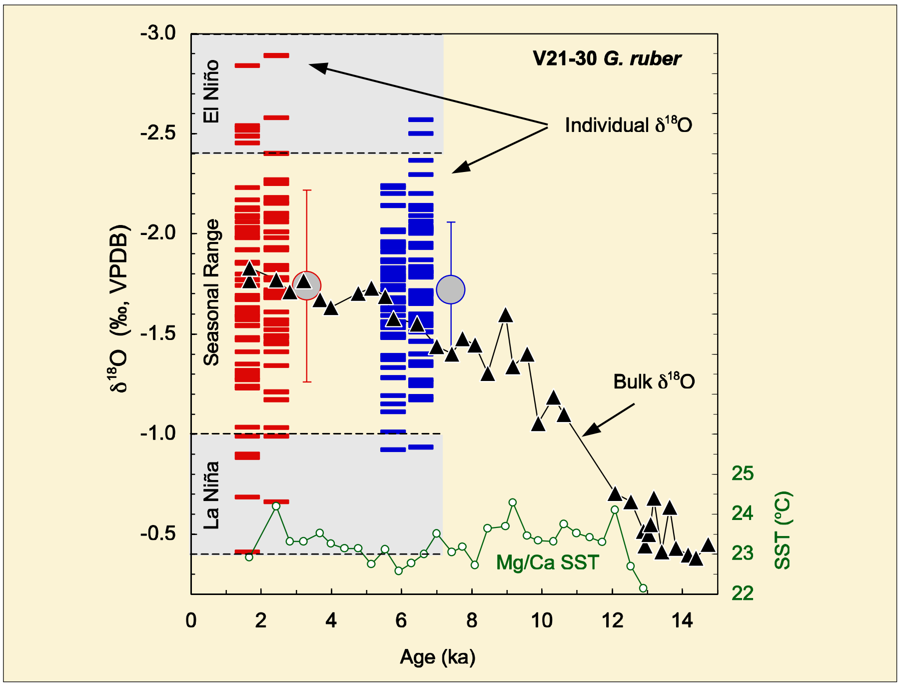

Figure 2: $\delta^{18}O$ of individual G. ruber from two late Holocene (red bars) and two mid-Holocene (blue bars) samples from core V21-30 (Koutavas et al., 2006). Downcore $\delta^{18}O$ data on bulk G. ruber (black triangles) and Mg/Ca SST estimates (green circles). Filled circles with error bars are the mean and standard deviation of the pooled late Holocene (n=93) and mid-Holocene (n=96) individual analyses. The standard deviation of the mid-Holocene data (σ=0.34) is 30% less than the late Holocene (σ=0.48), and the total variance (σ^2) is 50% less, consistent with weaker ENSO.

To help address these questions and further refine our view of ENSO variability we developed a new approach based on $\delta^{18}O$ distributions of individual G. ruber foraminifera with a life span of approx. 1 month (Fig. 2). Thus far, results from core V21-30 near the Galapagos Islands corroborate a mid-Holocene reduction in $\delta^{18}O$ variance, apparently due to both fewer El Niño and La Niña events. This suggests that the Mg/Ca SST trends do not merely reflect the integrated influence of weaker ENSO on the mean climate. Rather, it seems more likely that ENSO itself adjusted to the background climate shift and, in this regard, the ITCZ may again have been instrumental. Two scenarios seem plausible: (1) the northward-shifted summer ITCZ lengthened the upwelling season (presently August-September) and in so doing inhibited the growth of El Niño, which typically occurs between September and November; or (2) an expanded seasonal ITCZ range (more northerly summertime position) reinforced the annual cycle, causing it to act as a pacemaker-regulator of SST, inhibiting interannual anomalies. Whichever the case, the interaction of the seasonal and interannual modes is a crucially important factor for the long-term ENSO modulation. Annually resolved corals (e.g. Tudhope et al., 2000) remain our best hope for investigating this relationship and their potential should be aggressively pursued. But the ubiquitous availability of foraminifera in continuous deep-sea sediments may be a tantalizing alternative until sufficient coral records become available, and this approach also ought to be exploited more rigorously.

Although still blurry, the picture is gaining clarity and it now seems undeniable that a strong relationship between ITCZ position, equatorial SSTs, and ENSO operated throughout the Holocene. While it is likely that this dynamic system will be sensitive to future perturbations from greenhouse forcing, it is somewhat disconcerting that our understanding of its past behavior is still so rudimentary that any prediction for the future is fraught with uncertainty.

Note

Data will data will be available from the NOAA Paleoclimatology website at http://www.ncdc.noaa.gov/paleo/paleo.html

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Long-term climatic variations in central Asia and the deVries solar cycle

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It is commonly believed that the ~200-year deVries cycle is one of the most intense solar cycles (Vasil'ev et al., 1999, Wagner et al., 2001). This is evidenced, for instance, by the occurrence of pronounced solar activity minima (Maunder, Spörer, Wolf) in approx. 200-year intervals during the last millennium. The temporal coincidence between the Maunder (AD 1645-1715), Spörer (AD 1416-1534), and Wolf periods (AD 1280-1350) and the expansion of Alpine glaciers indicates a climatic response to these solar minima (Eddy, 1976). A similar conclusion was recently inferred from an analysis of glacier expansion in Alaska (Wiles et al., 2004).

Here, we aim to reveal the deVries cycle in Central Asia by analyzing tree-ring growth data of *Juniperus turkestanica* trees from upper timberline sites in the Tien Shan Mountains, and comparing the obtained paleoclimatic record with the ~200-year wavelength solar variations during the last millennium.

To assess long-term climatic fluctuations during the last millennium, tree-ring width variations of *Juniperus turkestanica* (ΔR) growing above 2800-2900 m asl were considered. Trees at these locations in the Tien Shan Mountains can reach ages of 2000 years. Analyses of the climatic signal of Juniper tree-ring width data reveals a clear June-July temperature signal, and no significant influence by precipitation variations (Mukhamedshin and Sarbaev, 1988). Similar conclusions on the dominant influence of summer temperatures on ring-width formation of *Juniperus turkestanica* were made by Maksimov and Grebenyuk (1972) and Esper et al. (2003). Accordingly, the analysis of long-term Juniper ring-width variations, and a comparison with solar activity variations (Δ14C in our case) allow us to investigate potential relationships between long-term changes in solar activity and summer temperatures in Central Asia.

To reliably separate out ~200-year fluctuations in ΔR for *Juniperus turkestanica*, we analyzed long-term ring-width records developed for different locations in the Tien Shan Mountains by independent research teams: Maksimov and Grebenyuk (1972), Mukhamedshin and Sarbaev (1988), and Esper et al. (2003a). All chronologies reached back to at least 800 years; hence, records are much longer than the periodicity of interest of about 200 years.

Figure 1: Map showing the locations of the tree-ring sampling sites in the Tien Shan Mountains. The green circle marks the site collected by Maksimov and Grebenyuk (1972), the violet bold line the site collected by Mukhamedshin and Sarbaev (1988), and the red rectangle the site used in Esper et al. (2003b).

- The chronology of Maksimov and Grebenyuk covers the time interval from AD 1170 to 1970. Samples were collected in Tajikistan on the northern slope of the Zeravshan range, at an altitude of

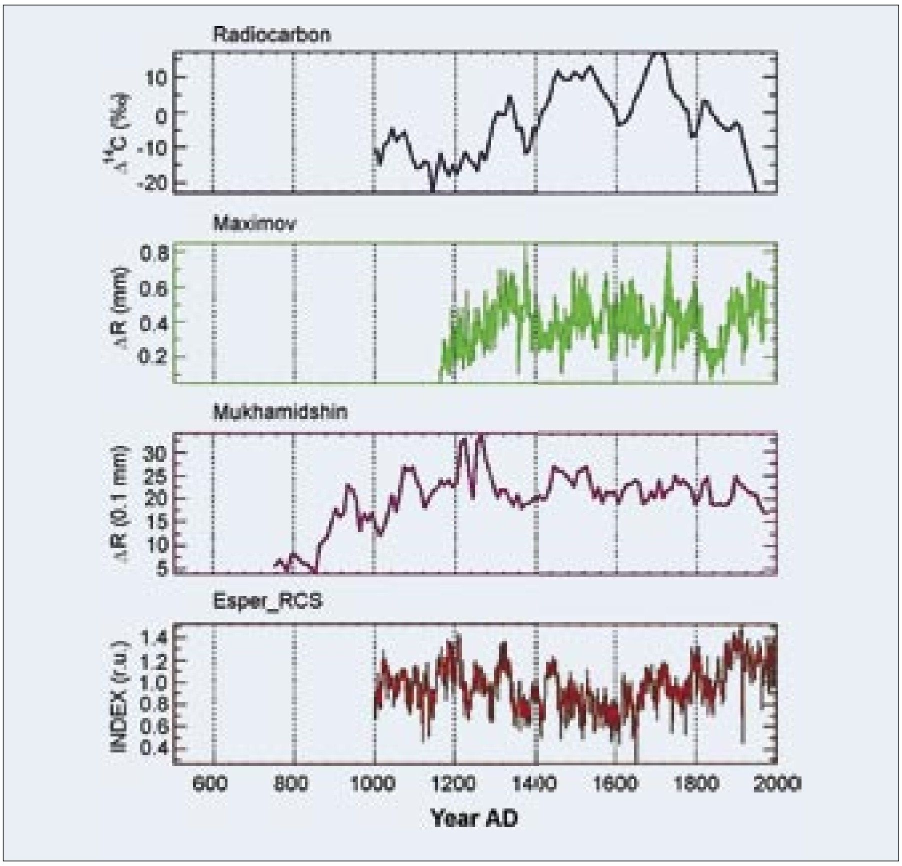

Figure 2: From top to bottom: variations in 10-year averages of $\Delta^{14}C$ (Stuiver et al., 1998); tree-ring widths records (ΔR) by Maksimov and Grebenyuk (1972); Mukhamedshin and Sarbaev (1988) (averaged over 10-year intervals); Regional Curve Standardization (RCS) chronology (index) by Esper et al. (2003a).

Table 1: Correlation coefficients (R) and the phase shifts Δt (years) between the records presented in Fig. 2

	Corr. Coef(R)	Δt (years)
Δ ¹⁴C-Maksimov	0.82	40
Δ ¹⁴C-Mukhamedshin	0.57	0
Δ ¹⁴C-Esper_RCS	0.52	0
Maksimov - Mukhamedshin	0.74	-60
Maksimov - Esper_RCS	0.75	-20

3500 m, about 1.5 km from the Matcha glacier (39.5°N, 70.7°E).

- The chronology of Mukhamedshin and Sarbaev (1988) covers the interval from AD 750 to 1972. It is based on data from trees older than 650 (up to 1250) years. Samples were collected in southern Kirghizia on the northern slope of the Alay range, at elevations above 2900 m (39.9°N, 72.5°E). Both the Maksimov and Grebenyuk (1972), and Mukhamedshin and Sarbaev (1988) records were developed using tree discs rather than core samples.
- The third dataset used in this analysis is the Regional Curve Standardization (RCS) detrended chronology by Esper et al. (2003b), integrating Juniper core samples from several high-elevation sites (>2900 m asl) in the Alay range, southern Kirghizia (39°50'-40°12'N, 71°30'-72°37'E). This record spans the past millennium. All tree sites are shown in Figure 1.

To analyze long-term solar activity variations, concentrations of cosmogenic radiocarbon ($\Delta^{14}C$) derived from tree-ring data (Stuiver et al., 1998) were used. For the last millennium, the $\Delta^{14}C$ data were averaged over 10-year intervals.

The $\Delta^{14}C$ record and the three ΔR chronologies are shown in Figure 2. These data were subjected to band-pass filtering in the range of periods 180-230 years and wavelet transformation (Morlet basis) in the range of periods 100-300 years. Band-pass filtered results are shown in Figure 3.

The band-pass filtered tree-ring chronologies of *Juniperus turkestanica*, that in essence represent variations in summer temperatures in Western Central Asia, and of the $\Delta^{14}C$ curve all indicate pronounced ~200-year oscillations (Fig. 3). It is also evident that a decrease in the period of quasi-200-year variations during the last millennium is observed in both the $\Delta^{14}C$ and dendrochronological data. The dynamic spectra of changes in solar activity and climatic processes estimated from millennium-long tree-ring records in Central Asia are similar, pointing to potential interrelations.

Figure 3 also shows that the band-pass filtered (tree ring and $\Delta^{14}C$) records are quite synchronous. However, there is a phase shift between them (see Table). This shift could potentially be due to the reservoir effect in $\Delta^{14}C$ deposition in tree rings (Dergachev, 1977). Alternatively, local climatic conditions (proximity to glaciers, etc.) might affect the phase relation between the curves.

If we take the phase shift into account, the curves shown in Figure 3 indicate high correlation coefficients in the 180-230 year period range (see the Table). For the $\Delta^{14}C$ curve and chronology of Maksimov and Grebenyuk, this coefficient reaches 0.82. High correlation coefficients are another indicator (in addition to the dynamic spectra) suggesting interrelation between solar activity and climatic processes.

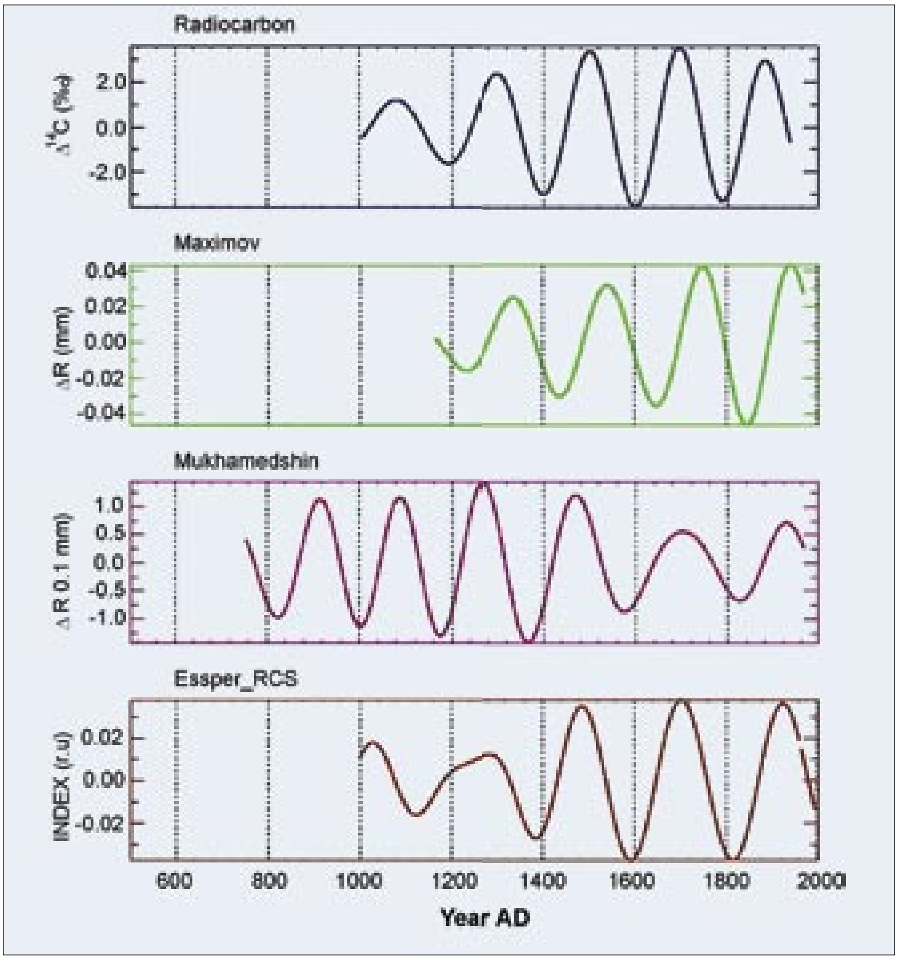

Figure 3: Results of 180-230 year band-pass filtering the data shown in Figure 2; (from top to bottom) variations in 10-year averages of $\Delta^{14}C$ (Stuiver et al., 1998); variations in tree-ring width (ΔR) chronology of Maksimov and Grebenyuk (1972), and Mukhamedshin and Sarbaev (1988); RCS chronology (index) by Esper et al. (2003a).

Conclusions

Our analysis of long-term dendrochronological data from Western Central Asia Juniperus turkestanica tree-ring data, developed by three independent research teams, demonstrates the presence of ~200-year climatic variations over the past millennium. These variations show a high correlation (up to R= 0.82) with a similar periodicity (deVries period) in solar activity inferred from radiocarbon data ($\Delta^{14}C$).

Acknowledgements

We thank Prof. Olga Solomina and Dr. Olga Kozyreva for discussion of results. This work was supported by the European Commission (Program INTAS, Projects DENDROLAB and CAMBIFORRUS), the Russian Foundation for Basic Research (projects 06-04-48792a, 06-02-16268a, 06-05-64200a), the Russian Academy of Sciences (Program N 16 "Changes of Environment and Climate"), and the Swiss National Science Foundation (NCCR-Climate).

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Regional climate variations in south America over the late Holocene

Malargüe, Argentina, 4 -7 October 2006

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LOTRED-SA (Long-term climate reconstruction and diagnosis in South America) is a new PAGES research initiative (PAGES News, Vol. 13 No. 2). This collaborative effort aims at collating existing data sets to produce a comprehensive high-resolution multi-proxy reconstruction of regional climate in South America over the last few millennia.

Hosted by the city of Malargüe, Argentina and organized by PAGES, the Instituto Argentino de Nivologia, Glaciologia y Ciencias Ambientales (IANIGLA) and the University of Bern, Switzerland, LOTRED-SA held its first science conference from 4-7 October 2006. 133 scientists from 17 countries (mainly from Argentina, Chile, Brazil, Switzerland and USA, among them many members of the PAGES Scientific Steering Committee) joined for review keynotes, and oral and poster presentations of new paleoclimate data sets and research activities.

The objective of the conference was to gather experts from different fields in climate dynamics, diagnosis and paleoclimatology (data and models) to review the existing knowledge and data sets, to discuss the interpretation of natural and documentary proxy data, to search for calibration and quantification techniques of proxy data sets in South America, and to discuss the implementation plan for the PAGES Research Initiative LOTRED-SA. The long-term goal and vision of this collaborative effort is to work towards a comprehensive view of regional climate variability and environmental change back in time (ca. 1000 years), and to produce a gridded data set of climate variables from high-resolution (sub-decadal) multi-proxy time series.

The conference sessions were organized along the lines of the research plans of LOTRED-SA, PAGES/CLIVAR and PAGES Focus 5 “Past Ecosystem Processes and Human-Environment Interactions”. Accordingly, the presentations were grouped into sessions dealing with present climate variability; past climate variability inferred from historical documents; tree rings; lake and marine records; high-resolution pollen records; ice cores; and glacier fluctuations; speleothems; and human-climate interactions in South America during the past three millennia.

Walking like a dinosaur - making big steps: impressions from an evening fieldtrip. Dinosaur sceptics up left: glaciologists Patrick Ginot and Christoph Kull, biologist Antonio Maldonado.

The most noteworthy outcomes were: (i) In contrast to the general perception, there is actually a considerable number of high-quality data sets available, mainly from tree rings and documentary data sources. (ii) Besides sampling resolution and dating, the main challenges for most natural proxy archives (ice cores, lake and marine sediments) are the calibration with meteorological time series and the quantification of paleoclimate information. (iii) Increasing sampling resolution, discriminating climate from land-use effects in proxies, and quantifying the paleoclimate signal remain the main challenges for paleovegetation archives. (iv) The paleoclimate research community in South America is well connected, enthusiastic and ready to take collaborative leadership in the LOTRED-SA venture. It is very much hoped that other research communities in different regions of the world will follow the South American example.

The plenary of the conference agreed on the following implementation plan:

1) Early 2007: Meta-data database of existing proxy data sets established. The conference proceedings including review papers and original research articles will be the first intermediate product (special issue in Palaeo3).
2) 2007: Evaluation and selection of data sets, geographic areas, time window and resolution for the multi-proxy reconstructions.
3) 2007-08: Construction of a shared and protected database with proxy data sets, and evaluation/discussion with the authors. The results will be presented in a special issue of the PAGES newsletter (ca. 2008).
4) 2008: Actual multiproxy reconstruction and joint publication by all the contributors.
5) Ca. 2009: Next science meeting with PAGES, possibly in the context of the 3rd PAGES Open Science Meeting.

Guidelines for collaboration and contributions to LOTRED-SA are available at www.pages-igbp.org/science/initiatives/lotred-sa/ or by contacting one of the authors or the PAGES office.

Past hurricanes

Lafayette, Louisiana, USA, 25 - 28 September 2006

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An update of what is known about past hurricanes (large storms, typhoons, tropical cyclones) and their impact on humans is direly necessary in order to improve preparedness plans. This effort is really timely as a controversy about the nature of the impact of global warming on the number and magnitude of hurricanes in the Gulf Coast area is ongoing. The hurricane season of 2005 in the Gulf Coast was intense, while 2006 was calm. In order to obtain a record longer than the instrumental one, a combination of historical sources and geological sequences need to be tackled. They each bring their own type of information and each has their limitations. The impact of these natural hazards on past ecosystems and societies, and how they recovered, is an integral part of the project.

PAGES and UNESCO-IGCP 490 (The role of Holocene environmental catastrophes in human history) workshops at the last Gulf Coast Association of Geological Societies meeting (25-28 September 2006) in Lafayette, Louisiana, USA, brought together 20 of the best scientists in the field from 13 different countries. Three oral sessions, one poster session and two days of field trips (the Mississippi delta and New Orleans itself) illustrated the difficulty and relevance of this research from a multidisciplinary perspective (within the fields of history, meteorology, geology, geography, geomorphology and anthropology). Different parts of the world were represented in the talks, including the Gulf Coast, Atlantic coasts of Europe and North America, Mediterranean Sea, South Pacific Ocean and Indian Ocean.

We had a fruitful workshop with debate on six key topics:

(1) Signature of hurricanes in the sedimentary record

In the geological record, the distinction of deposits left by hurricanes and tsunamis remains difficult. It is of primary importance to study parts of the world where both phenomena occur in order to increase the establishment of a specific signature.

(2) Paleo-frequency of hurricanes

The frequency reconstruction can be tackled by the study of available high-resolution records, such as historical data, corals, stalagmites and lacustrine varves. Most of those proxies are under-exploited.

Figure 1: Sand and debris accumulation against a house, caused a levee breach (by Hurricane Katrina in 2005 in New Orleans, USA). People's heads at the back for scale. Photo taken one year after the event. (Photo: S. Warny).

(3) Paleo-intensity of hurricanes

Intensity reconstruction is a more difficult issue than frequency. It is probably impossible to reconstruct absolute intensities. However, the relative intensity in one spot is usually what is reconstructed. Historical archives may offer a valuable contribution, since often the destructive impact is recorded.

(4) Geographical extent of hurricanes

Reconstruction of geographical extent is very arduous because of the fairly small geographical extent of storms. Some historical archives, in the form of letters from affected towns that have contacted the metropolis to receive aid, exist.

(5) Forecast of hurricanes

At present, the forecast of individual events beyond a few days in advance is impossible but there is more promise to work at the level of hurricane seasons and periods of higher energy, for example ENSO in the Southern Pacific.

(6) Effect of hurricanes on past populations

In some countries, there is little long-term impact from large storms, while in others, where food and water resources are affected, the impact is much larger and longer lasting. In some places, tradition has integrated the danger of hurricanes and people do not settle in unsafe places.

The need for the creation of a scientific association dealing with past large storms was expressed, since no multidisciplinary international association exists. Possible future venues for special sessions and meetings were proposed, such as a special session at the next INQUA congress in Cairns, 2007, and a contribution to the IYPE.

Acknowledgements

The meeting was funded by PAGES and UNESCO-IGCP 481. GCAGS local organization (Mary Broussard and co-organizers) also helped with sponsorship for logistical aspects of the meeting.

The 8.2kyr event

PAGES/CLIVAR workshop, Birmingham, UK, 28 October 2006

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The PAGES/CLIVAR Intersection panel has highlighted climate events around 8200 years ago (Rohling and Pälike, 2005; Morrill and Jacobsen, 2005) as a key period that may allow paleoclimate data and analysis to influence model development and understanding of future projections for the North Atlantic. In order to further that goal the panel recently organized a workshop on the 8.2kyr event to better synthesize our understanding of the event. The workshop brought together specialists in the ice core record, ocean sediments, terrestrial proxies and modelers from both the EMIC and GCM communities. The existence of a unique event at around 8200 yr BP around the North Atlantic is no longer in question, but there remain uncertainties about how widespread the anomalies were and how well the length, duration and character of the event can be characterized. The currently favored hypothesis is that these anomalies were related to a transient change in the North Atlantic overturning circulation, possibly triggered by the final drainage of Lake Agassiz (Barber et al., 1999; von Grafenstein et al., 1998), so direct evidence from oceanic proxies for such an event are particularly sought after. Unfortunately, the abruptness of the event, poor age control, and the potential for opposing influences on the carbonate isotope record have made extracting oceanic counterparts to the terrestrial anomalies particularly challenging. The workshop agenda reflected these questions and was designed to :

a) Highlight what is known from the least ambiguous proxies.
b) Assess what it is meaningful to conclude from other evidence.
c) Look for potential problems in the Lake Agassiz hypothesis.
d) Agree on key questions that need to be addressed in the future.

The best evidence for a widespread and unique event at this time comes for the Greenland ice cores. New, extremely high-resolution ice core records were presented and clearly demonstrated that there was a coherent event whose peak lasted a few decades, that was distinct from all other events in the Greenland records for the Holocene (Fig. 1) . Layer counting indicates that while the whole event seems to have lasted around 160 years, the peak anomalies lasted only 60 to 70 years—underlining the challenge of finding this event in coarser resolution proxies. Evidence for a distinct event that was similarly unique in the Holocene in regions far from the Central and North Atlantic was more ambiguous. With a strict definition, and only using high-resolution and exceptionally well-dated records, clear evidence is restricted to the circum-North Atlantic region. New records from the British Isles, Newfoundland and Norway, for instance, were presented that have clear 8.2kyr event signatures. However, while there are hints of possibly synchronous excursions in lower resolution, less well-dated records, it is necessary to be extremely conservative in attributing them to the same event, to guard against 'false positives' arising simply from noise or longer term unrelated variations.

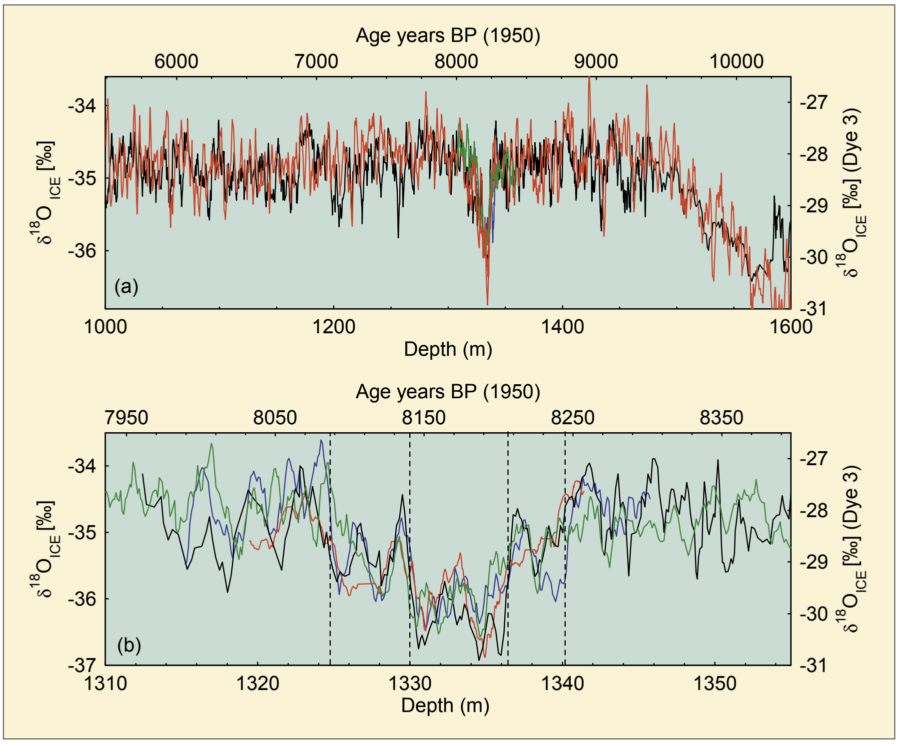

Figure 1: Four Greenland ice cores (Dye3, GISP2, GRIP and North GRIP) show a unique signature of an event at 8.2kyr BP. Each ice core record (on a common time/depth scale and scaled to the Dye3 isotope ratios) contains many common features found in all, however, at the timescale of individual years they do show differences that cannot be easily interpreted. The dashed lines denote where the records persistently depart from (and return to) one sigma and two sigma deviations from the preceeding period, usefully encapsulating the length of the detectable event (around 160 years) and its peak period (60-70 years) (figure courtesy of Liz Thomas and Eric Wolff).

In the North Atlantic ocean, new and varied sediment data seem to indicate concurrent changes in the circulation, particularly in transport-related proxies such as the sortable-silt fraction, but with varied timing and duration that still requires analysis (Ellison et al., 2006). Indeed, dating problems due to potential reservoir age uncertainty and bioturbation still limit our ability to easily interpret the ocean records. Overall, the ocean data provide a complex and not easily interpretable picture and in that sense are analogous to the similarly complex picture of the North Atlantic circulation variability provided by direct observations over recent decades.

Modelers have started to use the 8.2kyr event as a test case for examining the models' response to freshwater forcing, and are now using freshwater amounts and input locations that are much more relevant to this event than had been done previously with idealized 'hosing' experiments. Workshop participants discussed results from intermediate models as well as from GCM groups (The Hadley Centre, NCAR and GISS). These relate to the somewhat stochastic nature of the response to Agassiz-sized forcings, the impact of ocean changes on relevant proxies (water isotopes, methane emissions, aerosols) and the importance of preventing Labrador Sea deep water production (which is not thought to have been initiated prior to about 7 kyr BP).

Despite these initially encouraging results, significant problems remain. The most important and one that was repeatedly raised was that of chronology. The offset (around 200 years) in the terrestrial dates for the Agassiz drainage and the ice core chronologies, while within error bars, is still quite significant. Other carbon-dated records in the ocean sediment or on land are affected by a carbon-dating plateau around this time, which suggests the need for more work on alternate dating techniques, such as tephrology, for cross-correlating the different records. Other questions are more subtle. The North Atlantic has a very complex and dynamic circulation on decadal to multi-decadal timescales, and modern observations do not support the notion that all of this variability can be associated with a single quantity (such as the overturning streamfunction). Fitting the disparate ocean records into a wider and more complex picture is not easy and work is clearly required to improve that. And finally, improved and higher resolution data from the tropics and sub-tropics—particularly in Asia—are going to be needed to resolve the amplitude of any far-field response. The latest results and initial modeling work strengthen the panel's initial view that this event is a key target for Holocene paleoclimatology and that it may prove helpful in providing tests of climate models and influencing their development. That potential has yet to be fully realized.

Acknowledgements

This paper grew out of discussions at a workshop on the 8.2 kyr event in Birmingham, UK organized by the PAGES/CLIVAR Intersection Panel with funding from US and Swiss NSF. We thank PAGES and RAPID (NERC) for faciliating the meeting.

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IGBP-SCOR Workshop: Ocean acidification — modern observations and past experiences

Lamont-Doherty Earth Observatory of Columbia University, USA, 28-30 September 2006

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This workshop was the centerpiece of the Fast-Track Initiative (FTI) on Ocean Acidification of the International Geosphere-Biosphere Programme (IGBP) and the Scientific Committee on Oceanic Research (SCOR). The FTI is about exploring how we can learn from past changes in the Earth system to better understand the consequences of ongoing ocean acidification, and involves several projects with a marine focus (GLOBEC, IMBER, LOICZ, SOLAS, PAGES and IMAGES).

The workshop was attended by 65 international participants (Fig. 1). It was co-sponsored by IGBP, SCOR, and PAGES, and organized by the PAGES IPO and local hosts at Lamont. The goals of the workshop were to:

1) bring together researchers on modern ocean acidification with researchers investigating relevant events in Earth history and
(2) explore how paleo-studies can shed light on the consequences of fossil-fuel CO_2 release into our environment.

A series of overview talks, posters, and breakout-group discussions stimulated cross-disciplinary thinking between paleo and modern perspectives, and among chemical, geological, and biological researchers, as summarized below:

Modern observations ...

The rates and amounts of CO_2 currently being emitted exceed those inferred for at least the past 50 million years, and possibly much longer. Much of this CO_2 is being absorbed by the ocean, where it is causing changes in the carbonate chemistry of seawater. Today, the surface oceans are supersaturated with respect to aragonite and calcite. However, the degree of supersaturation is declining, and the saturation horizons are migrating toward the ocean surface. The fundamental chemistry of human-induced ocean acidification is well understood but we are unable to predict how marine organisms will be able to adapt to ocean chemistry changes. The most optimistic view is that for organisms with short generation times, micro-evolutionary adaptation could be rapid and that species adversely affected by high CO_2 could be replaced by more CO_2-tolerant strains or species, with minimal ecological impacts. The most pessimistic view is that CO_2-sensitive groups (e.g., marine calcifiers) will be unable to compete ecologically with profound ramifications up the food chain, including widespread extinctions.

The consequences of ocean acidification appear to be clearest for corals, with most studies suggesting a linear relationship between coral calcification rate and aragonite saturation state. Coccolithophores and foraminifera generally exhibit

Figure 1: Group photo of the participants at the IGBP-SCOR Workshop on "ocean acidification" in front of "Lamont Hall".

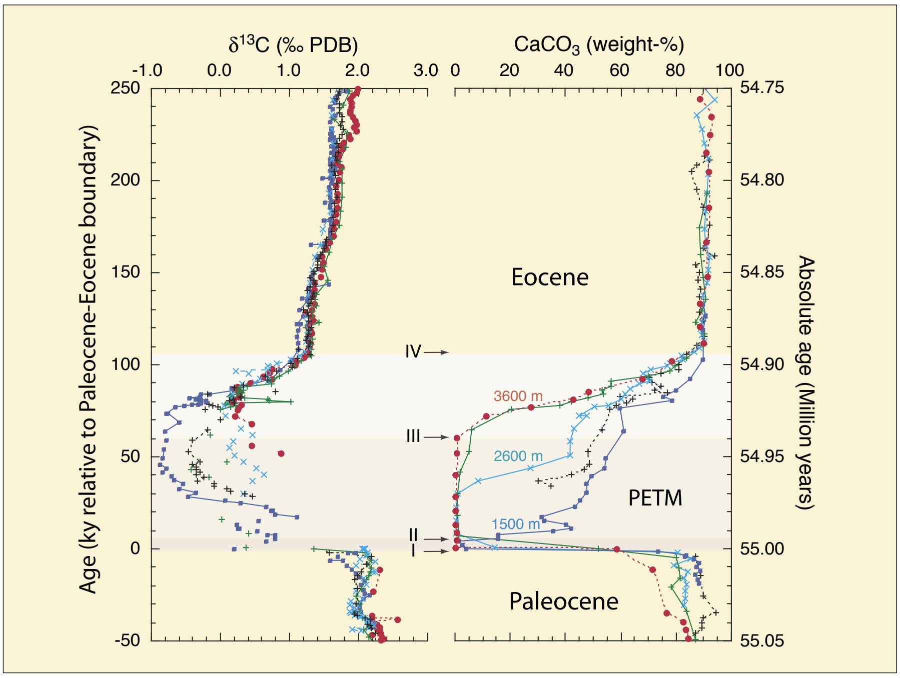

Figure 2: Geochemical records across the Paleocene Eocene Thermal Maximum (PETM) from a depth transect (paleodepths between 1500 and 3600 m) of five Ocean Drilling Program sites in the South Atlantic. The PETM is marked by a substantial negative carbonate isotope excursion. Note the rapid and massive drop in calcium carbonate content for all sites in the lowermost Eocene (marked I); the return of the CCD after roughly 5 ky at the shallow site (II); the return of the CCD to the deepest sites after only 60 ky; and the full recovery of the lysocline at 110 ky after the excursion (marked IV). After Zachos et al., Science 308, 1612-1615, 2005.

a weaker calcification response. However, laboratory and field experiments have involved only small numbers of individuals and populations over relatively short durations, and provide little basis for predicting marine ecosystem responses on decade-to-century timescales. All observed effects are subject to large species-specific differences.

Experiments on calcification mechanisms indicate that some organisms control calcification by elevating saturation state at the site of calcification by up to 7 times that of seawater. Under this model, it might be hypothesized that small changes in saturation state of the seawater would have little effect on calcification rates. Hence, it is unclear why many organisms are highly sensitive to ocean chemistry changes.

... and past experiences

Given these large uncertainties in predicting the biological response to future ocean acidification, many are looking for answers from relevant parts of the geologic record:

For the industrial era, there is the potential to obtain records of the response of the marine sedimentary carbonate system to changing atmospheric CO_2 content, using archives such as deep-sea corals, rapidly accumulating sediments and molluskan shells.

For the late Pleistocene, records of atmospheric CO_2, paleo-pH and carbonate preservation demonstrate that at the onset of the industrial revolution, interglacial ocean pH and carbonate mineral saturation states were near the minimum (interglacial) values reached over the Pleistocene; hence, the industrial revolution occurred at a time when these ocean chemical parameters were particularly susceptible to being pushed outside the range of natural variability.

From the (less well-constrained) Cenozoic record of ocean carbonate chemistry there is no indication of any undersaturation of the surface ocean, at least since the Cretaceous-Paleogene (K-Pg) boundary (65 Ma). While data so far suggest that there is no exact past analog of present-day CO_2 emissions, discussion centered on how near-future scenarios might compare with the Paleocene-Eocene Thermal Maximum (PETM; 55 Ma, Fig. 2) and mass extinction events such as at the K-Pg boundary.

The carbon isotope shift at the PETM (Fig. 2) indicates that the amount of carbon released into the environment was comparable to what we could release over the next decades and centuries, but it is unclear whether these releases occurred over a short time or over many thousands of years (with hence reduced ocean chemical response).

Ecological responses to past episodes of ocean acidification are reflected in the paleoceanographic record. For example, disruptions in marine fauna at the PETM were primarily confined to bottom dwellers, with no distinct changes in pelagic groups, whereas during the K-Pg extinction event, many planktonic calcifiers went extinct and most corals died. It took millions of years for the calcareous plankton and corals to recover their biodiversity. Ocean acidification could have been a factor in these events but co-occurring factors (warming, darkness, ocean circulation) also likely played a role. A future challenge is to uniquely relate the paleobiological effects to causes.

Ocean carbon models and the sedimentological record both indicate that chemical recovery from projected CO_2 emissions will take several thousand to hundred thousand years (Fig. 2). Past extinction events indicate that biological recovery is measured in millions of years. This timescale is associated with chemical recovery of the environment, the evolution of new organisms, and the development of new food webs. Thus, both the chemical and ecological effects of CO_2 releases are basically irreversible on societal timescales.

Themes that surfaced repeatedly at the workshop included:

(1) Ocean acidification at the rate and magnitude projected for the coming decades represents a major risk to at least some marine ecosystems.
(2) Effects of acidification will differ across different marine environments but cannot be determined with any certainty based on our present understanding.
(3) Research is needed to assess the consequences of ocean acidification, including a better understanding of present, past and future changes in ocean carbonate chemistry, and the biotic responses to these changes.
(4) It is important to improve our communication to policy makers of the risks associated with ocean acidification, as these risks may provide motivation for rapid reduction of CO_2 emissions.

Workshop materials including the program, abstracts, breakout-group summaries, and many of the poster and oral presentations can be found on the FTI-website (http://igbp-scor.pages.unibe.ch/). PAGES intends to further provide paleo-perspectives on marine biochemical changes in its new Focus 3, which is currently being established.

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Reconstruction of past Mediterranean climate: Unexplored sources of high resolution data in historic time

1st MedCLIVAR Workshop, Carmona, Spain, 8-11 November 2006

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Figure 1: Participants at the 1st MedCLIVAR workshop.

This workshop was the first in a series of five meetings planned by MedCLIVAR (www.medclivar.eu), which is a program funded by the European Science Foundation (ESF) aiming to coordinate and promote research on different aspects of Mediterranean climate. The main MedCLIVAR activities include: (1) reconstruction of past climate, (2) description of patterns and mechanisms characterizing space-time variability, (3) comparisons of coupled climate model simulations with empirical reconstructions, (4) seasonal forecasting, and (5) identification of the forcing responsible for the observed changes.

The workshop was attended by 64 researchers from 15 countries (Fig. 1), 15% being PhD students. The main purpose of the meeting was to identify sources of early instrumental data, and natural and documentary climate proxies, which had not been previously explored but which are relevant for the reconstruction of climate in the Mediterranean region during past millennia. The first session reviewed the availability of documentary sources in the larger Mediterranean region, with reports from different countries and archives. The second part of the workshop analyzed the availability of natural archives in the area, such as tree-rings, lake sediments, speleothems and mollusk shells, and their suitability to reconstructions of different climate parameters such as temperature, precipitation or drought. Several examples of modeling past Mediterranean climate were shown in the third session, with emphasis on the comparison between model outputs and proxy evidence.

The main conclusions can be summarized as follows:

The Mediterranean region is rich in natural and documentary proxies of past regional climate. They resolve different temporal and spatial scales and reflect a wide range of climate parameters (SST, salinity, temperature, precipitation, sea level, geochemistry, etc). However, the currently available proxy data sets are not sufficiently dense to reconstruct climate with a high spatial variability as would be required for the Mediterranean basin. The main gaps in information come from Northern Africa, the Eastern Mediterranean and the Balkans.

There are numerous ongoing initiatives from different research teams to retrieve information from documentary collections and natural proxies but there is not a general strategy to search data and proxies on a basin-wide scale. This should be the target of an interdisciplinary approach, with researchers from different fields collaborating towards a common understanding of past climate change of the last 1000 to 2000 years using high-resolution proxies.

The simulation of past climates is accomplished using models of different complexity: EMICs and full complexity GCMs. Comparison with proxies at the Mediterranean scale is based on the use of GCMs. Simulations of the last millennium climate are subject to limitations by model resolution, orography representation, parameterization, as well as to model and external forcing uncertainties but still can provide some interesting comparisons with climate reconstructions.

Exercises comparing documentary and natural proxies, and model outputs are scarce for the region. They should improve the quality of all types of data sets and models but should be compared with care, taking into account the uncertainties in the proxy reconstructions, the complexity in the transfer functions from proxy parameters to climate variables, and the internal variability of the models, which is highly dependent on the modeled variable.

The workshop was the starting point towards building a community working together on the past climate of the Mediterranean region, incorporating scientists and data from the north African and Eastern Mediterranean communities, and creating links between paleoscientists, climatologists, and modelers. The next step will be the creation of a web-supported meta-database to increase data interchange. The database will be hosted by MedCLIVAR and will be supported by PAGES.

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Call for contributions: general PAGES activities

All PAGES Newsletters now have an open section for general contributions. If you would like to contribute a "Science Highlight", "Workshop Report", "Program News", or an amusing "Tales from the field" story for the forthcoming April 2007 issue of PAGES News, please contact Thorsten Kiefer (kiefer@pages.unibe.ch).

The deadline is 28 February 2007.
Information and guidelines are available at:
http://www.pages-igbp.org/products/newsletters/instructions.html

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